Simulation Modeling as a Tool for Assessing the Impact of Inventory Control and Scheduling Policies in the Manufacturing of Specialty Steel

by

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Submitted to the Department of Materials Science and Engineering on January 16, 1998 in Partial Fulfillment of the Requirements for the Degree of Master of Science with Recommendation from the Department of Materials Science and Engineering

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Abstract

This thesis is the outcome of a six month internship at a specialty steel manufacturing company. Facing a specialty steel market characterized by increasing competition, decreasing prices and global over-capacity, this company has initiated significant cost reduction efforts.

This thesis focuses on cost reduction through improved control and scheduling of inventory in a recently modernized stainless steel manufacturing plant. An analysis of the level and variation of total work in process within the plant suggests the need for rules authorizing the release of work on the basis of system status rather than solely on the basis of a schedule. Because of the breadth of the product mix (there are over 100 different grades of stainless steel), and because of the variety of process routings and processing recipes, predicting the impact of alternate inventory control and scheduling policies is difficult. This thesis therefore presents an approach for assessing the impact of alternate inventory control and scheduling policies designed to improve the control of WIP and cycle time without sacrificing throughput.

To approach this problem, simulation modeling is presented as a tool that can accurately capture the complexity of steel manufacturing operations and that can therefore provide an environment in which controlled experiments can be performed. A method for extracting information from production records and for building simulation models is presented. This method is used to construct simulation models for two anneal and pickle lines. These models are shown to be accurate to within 1% in predicting the fraction of time spent on setups relative to the total production time. These simulation models accurately capture the impact of product mix and campaigning on production time, setup time and on the occurrence of setups.

Suggestions are given on possible improvements to the simulation models and on how to use them to investigate alternate inventory control and scheduling policies. Recommendations are made on additional problems that were uncovered as a result of the modeling analysis.

Thesis supervisor: Lawrence M. Wein

Title: Professor of Management

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1. Introduction

1.1 General Introduction

This thesis is the outcome of a six month internship at a specialty steel manufacturing company. The initial assignment for this internship was to investigate possibilities for reducing cycle time within a recently modernized stainless steel manufacturing plant. The plant contains 10 facilities:

Weld & Side Trim Line	2 Anneal and Pickle Lines
Sendzimir Mill	Temper Mill
2 Slitters	Splitter
Punch Press	Bundling Station

In addition to these facilities, a new cold rolling mill is expected to be operational in early 1999.

In the context of stainless steel manufacturing, and using the terminology of Hopp and Spearman [5], the components of cycle time are queue time, process time, wait for batch time, and move time (see definitions in section 11). For a typical coil going through a weld line, two anneal lines, a cold rolling mill, a slitter and a bundling facility, total queue time is on the order of two weeks, total wait for batch time, total process time and total move time are on the order of several hours. Hence, queue time typically accounts for more than 95% of the lifetime of a steel coil. Cycle time reduction therefore resides in the management of queue time.

Although the earliest due date sequencing rule is used to release coils from queues, the level and variation of queue time is well approximated by the level and variation of backlogs at facilities. Two figures allow to make statements about the degree of control of queue time within the plant. Figure 1 shows the backlog at three facilities during the period 1/1/97 through 12/4/97. From these graphs, we observe that the queues can vary in size by as much as a factor of two from their average value in less than a week. Crew scheduling and the impact of product mix on processing time are important contributors to this variation. Figure 2 shows the total work in process (WIP) within the plant for year 1997. This graph shows that for the period 5/1/97 to 9/28/97, work in process increased by more than 50% before returning to its original value. An analysis of the individual backlogs of all the facilities within the plant during the 1997 year shows that, at the 1 unit level, no facilities were ever significantly starved. Thus, no increase in throughput could have occurred as a result of the increase in WIP. Furthermore, this temporary increase in WIP translates approximately into an additional 4.5 million dollars held in the form of steel. In light of the amount of variation in the queue times and the apparent tardiness in the response to increases in WIP, these two figures suggest the need for a more dynamic inventory control and scheduling policy.

Inventory control and scheduling policies fall into two categories. Those in which the release of jobs is done on the basis of a schedule (scheduled based policies) and those in which the release of jobs is done on the basis of the state of the manufacturing system (state based policies). As described in section 2.3, the company uses a scheduled based policy. However, the implementation of a state based policy, in addition to the current scheduled based policy, may significantly improve the control of the level and variation of WIP.

The complexity in the routings that coils follow through the plant, the breadth of the product mix, and the wide range of processing recipes make it difficult to predict the impact of different state based inventory control and scheduling policies. More specifically, an analysis of the routings followed by coils through the plant (see Appendix 1) shows that no main routings exist. Furthermore, the breadth of the product mix not only contributes to a significant amount of variation in the processing times, which can cause bottlenecks to shift, but also to the occurrence and duration of setups. In light of these complexities, it is apparent that if analyses are to be performed to ascertain the impact of alternate inventory control and scheduling policies at low cost and with little risk, then a model of the manufacturing system is needed.

At the same time that the need for a modeling tool appeared, a project was initiated to determine how to prepare for the introduction of the new cold rolling mill. Questions were therefore raised on how to redistribute the product mix across the facilities in order to take full advantage of the capabilities of the new cold rolling mill, and on how to insure a smooth integration with the other steel manufacturing operations. Because of the breadth of the product mix and of the processing recipes, the lack of a tool for addressing these types of questions also indicated the usefulness of constructing a model of the manufacturing plant.

A simulation package was therefore purchased from Systems Modeling Corporation. As a result of this purchase, my project shifted towards understanding how to use production data to extract information needed to build simulation models and how to use the simulation software to build accurate simulation models of the facilities. Because most of the questions regarding the new cold rolling mill are about its impact on the anneal lines, my goal was to build models for the two anneal and pickle lines and for the cold rolling mill. This goal was partially fulfilled. Accurate models were built for the two anneal and pickle lines. Some difficulties were encountered in building the model for the Sendzimir mill.

1.2 Outline of Thesis

In section 2, we present an overview on inventory control and scheduling policies. The policy used by the company is also described. Section 3 describes the distinction between analytical and simulation models, and why simulation models are usually more appropriate for modeling real manufacturing systems. Section 4 describes the basic components of a discrete event simulation model. Section 5 describes the methodology used to construct the simulation models. Section 6 describes the annealing, pickling, and rolling processes. Section 7 and 8 present the models for the two anneal and pickle lines. Section 9 presents a model for the

Sendzimir mill. Conclusions and recommendations appear in Section 10. Definitions of terms that appear throughout this thesis are given in the definitions section.

For confidentiality reasons and to avoid divulging proprietary information, the specialty steel manufacturer is referred to as 'the company'. Similarly, the manufacturing plant studied in this thesis is referred to as 'the plant'. Furthermore, certain characteristics of figures or processing recipes may voluntarily be omitted.

2. Inventory Control and Scheduling Policies

Inventory control and scheduling policies are rules for moving jobs within a manufacturing system. These policies can be separated into two categories: state based policies and scheduled based policies.

2.1 Scheduled Based Inventory Control and Scheduling Policies

A schedule based inventory control and scheduling policy releases jobs on the manufacturing floor according to a schedule. This schedule is created by working backwards from the delivery date for the expected or actual demand of the final product. By scheduling the release of jobs, such policies typically attempt to control throughput and allow WIP to vary in response to unexpected changes in the manufacturing system. The most common of these policies are Material Requirements Planning (MRP), and Manufacturing Resources Planning (MRP II).

Material Requirements Planning distinguishes 'independent demand', the demand for the end product, and 'dependent demand', the demand for the components which come together to form the end product. In doing so, MRP recognizes that, while independent demand is subject to uncertainty, dependent demand depends deterministically on independent demand. Because of this relationship between independent and dependent demand, the production schedule for components is based on the delivery schedule for the end product. Thus, in its most basic form, MRP begins with the master production schedule (MPS) for the end product. Then, by going down each level of the bill of materials which describes the relationship of the various components to the end product, the MPS is revised according to the lead times of the components at the next level of the product structure. With this iterative process complete, a production schedule for all the processing stages is obtained.

Manufacturing Resources Planning (MRP II) takes the MRP approach and incorporates additional logic such as forecasting and capacity requirements planning (CRP). With the latter modification, the master production schedule is analyzed at each level of the bill of materials to insure that it is capacity feasible.

MRP and MRP II scheduling policies have several shortcomings. First, the master production schedule is assumed to be known with certainty. A remedy to this problem is to incorporate safety stock in the production schedule. However, as pointed out by Nahmias [8], the manner in which uncertainty transmits itself through complex multilevel production systems is not well understood. Secondly, the lead times, which are used to translate the master production schedule from one product level to another, are assumed to be constant. Finally, because of the occurrence of unexpected events in the manufacturing process, there are pressures to increase the planned lead times in order to meet delivery dates.

2.2 *State Based Inventory Control and Scheduling Policies*

State based inventory control and scheduling policies release jobs on the manufacturing floor according to the state of the manufacturing process. By defining work release rules that depend on the downstream congestion of the manufacturing system, state based policies control WIP, but allow throughput to vary in response to unexpected changes in the manufacturing system or external demand. Since variation in throughput is clearly undesirable, state based policies tend to put much greater pressures on the manufacturing system to minimize the occurrence of unexpected events. The most common of these policies is Just in Time (JIT), and a more recent innovation is Constant Work in Process (CONWIP).

Just in Time differs significantly from MRP in that the release of work is not through a master production schedule but by request from next level processes. JIT systems are typically implemented with a requesting system such as Kanban to facilitate the flow of information between workstations. In its most basic form, the requesting system requires operators to wait for cards from downstream workstations before processing a part. Despite the apparent simplicity of a JIT policy, significant pressures are put on the manufacturing system: Without low rejection rates, short setup times, and low failure rates, the throughput of the manufacturing process can be adversely affected by unexpected machine failures and unexpected fluctuations in demand. In this respect, the virtue of JIT is not implementing JIT but rather creating a manufacturing environment in which it can be implemented.

There is however a bigger principle at issue in implementing state based inventory control and scheduling policies. This principle is that excess inventory is the by-product of operating machines when they should not be operated regardless of whether they have been scheduled to do so, and regardless of what the desired efficiencies for the facilities may be. In other words, putting irrational emphasis on facility efficiency records and thinking that scheduled facilities should never be idle can lead to sub-optimal management of a manufacturing process as measured by the level of inventory and throughput. Consequently, the release of jobs on the manufacturing floor should always take into account the state of the downstream facilities. In light of these observations, a very practical implementation of state based inventory control and scheduling policies is through the implementation of WIP caps. The Kanban implementation of JIT is itself a WIP cap defined for each workstation.

A generalization of this approach, suggested by Hopp and Spearman, is to implement WIP caps to routings rather than single workstations, an approach which they refer to as Constant Work In Process (CONWIP). In a CONWIP system, a part may enter at the entry end of the routing only when a part is completed at the exit end of the routing. Arguably, CONWIP is simpler to manage than Kanban systems because fewer WIP caps have to be defined. Also, allowing WIP to distribute itself within a specified routing may be a desirable feature because this allows WIP to naturally accumulate around bottlenecks, thereby providing protection against starvation where it is needed. However, to my knowledge, CONWIP has yet to be tested in the stainless steel manufacturing industry.

2.3 Inventory Control and Scheduling Policy Currently Used at the Company

The company uses a schedule based inventory control and scheduling policy. It is a finite loading system similar to an MRP II system. When an order is received, a delivery date is estimated to within a week and the order is entered into the system. On the basis of the routing that the order will follow to be processed, the system calculates, using constant lead times for each facility, the dates at which the order will have to be processed at each workstation along the routing. The movement of work at individual facilities is then determined by the schedule produced by this finite loading system.

In order to meet the capacity limitations of the workstations, the finite loading system contains an accounting based model for the processing times of different products for all facilities. These models are based on IHPT rates (Inch Hours per Thousand pounds) specified for a given workstation, process type, grade, width range, and off-gauge range. The IHPT rates are updated yearly. However, because of learning curves in operating the facilities and improvements in processing recipes, the finite loading logic provides a 'factor x' which can be changed throughout the year to make adjustments to the IHPT rates on the basis of differences between standard values and year-to-date values. In addition to the 'factor x' fudge factor, the total number of hours that can be scheduled on a facility are adjusted to include unexpected delays, unexpected added operations and reworks.

2.4 Optimal Inventory Control and Scheduling Policy

Schedule and state based policies are means for reaching equally desirable but conflicting ends: minimize work in process and maximize throughput. On one hand, scheduled based policies directly accommodate customer due dates to maximize throughput and on-time delivery, but have to be forced to respond to unexpected changes in the plant (by recalculating the master production schedule). Furthermore, the pressure to maximize on-time delivery may cause lead times and therefore WIP to be inflated. On the other hand, state based policies directly respond to unexpected events, but must be forced to accommodate customer due dates (by using overtime to compensate for the loss of production). An optimal policy is therefore a hybrid combination of schedule and state based policies. In the context of an hybrid MRP system, a job is scheduled to be released according to the master production schedule but is voluntarily delayed because of congestion in the downstream manufacturing process. In the context of a hybrid kanban system, a card authorizing the release of a job is ignored because of an expected decrease in demand for the component.

Since the company uses a scheduled based finite loading system to control the release of jobs onto the factory floor, I proposed to initiate efforts to investigate how to implement elements of a state based policy with the objective of creating a hybrid system. The need for elements of a state based inventory control and scheduling policy resides on the following two observations. As discussed in the Introduction, Figure 1 shows that backlogs can vary by as much as a factor of two from their average value within a week. Secondly, Figure 2 suggests that there exists a lack of responsiveness in the inventory control system since it took over four months to reduce a 50% increase in WIP whose occurrence could not have resulted in an increase in throughput. I therefore initiated a simulation modeling effort in which the implementation and impact of WIP caps, designed to respond to unexpected events in the downstream manufacturing process, can be ascertained and can be tailored to the characteristics of specialty steel manufacturing. There are two additional reasons to justify building a model of the manufacturing system.

First, real world inventory control problems are often too complex to be studied through mathematical analysis. Computer based simulation is an alternate tool for comparing the impact of different inventory control strategies. Although both deterministic and stochastic problems can be addressed using simulation, simulation modeling has the virtue of being well designed to deal with elements of randomness.

Secondly, the implementation of elements of state based policies into the current scheduled based inventory control and scheduling policy is not trivial. In the context of a manufacturing system characterized by a broad product mix and many different processing recipes, it is not at all clear how WIP will distribute itself when WIP caps are applied to routings rather than individual facilities. Furthermore, it is unclear what effect WIP caps have in circumstances where the bottleneck facility can change as a function of product mix, and where products can follow many different routings.

3. Simulation Modeling

3.1 Definitions

A system is defined as a collection of objects, people or machines which interact together toward the accomplishment of some logical end. The state of a system is defined as the collection of variables necessary to describe the system at any given time.

Examples of systems are: manufacturing plants, banks and teller windows, a freeway system, a computer network. Examples of state variables are: the status of facilities (operational or under repair), the queue lengths at bank tellers, the number of cars on a freeway, the speed of servers in a computer network.

3.2 Why Simulation?

(a) Why Model a Manufacturing System?

A model of a manufacturing system provides an environment in which controlled experiments can be performed. For example, a model can help quantitatively predict the impact of adding a machine to the productivity of a manufacturing process. The sensitivity of important system quantities, such as throughput and work in process, can be measured against changes in system parameters, such as frequency of machine failures or queue sizes. Two types of models may be constructed to analyze the properties of a manufacturing system: analytical and simulation models.

(b) Analytical Models

If the relationships governing a manufacturing system are simple, a model may be constructed using analytical methods. Typically, such models involve equations of the form

$$prob[S(t+1)=i]=\sum_{j} prob[S(t+1)=i \mid S(t)=j]\cdot prob[S(t)=j]$$

which express the probability that the manufacturing system is in some state i at time t+1 as the sum of the product of the transition probabilities and the probability that the manufacturing system was in some state j at time t. For example, this equation might express the probability that a machine is operational at time t+1 given that it was either under repair or operational at time t.

The complexity of real manufacturing systems may render the analytical approach impractical. To understand this, simply consider that to calculate the steady state behavior of a manufacturing system, the number of equations needed is of the order of the number of states that the system can be in. Thus, for a simple system of k machines where each machine can be in two states (operational or under repair) and where the inventory space between machines is of maximum size N, the total number of states the system can be in is

$$M = 2^k \prod_{i=0}^{k-1} (N_i + 1).$$

As pointed out by S.B. Gershwin [3] in Manufacturing System Analysis, for a 20 machine system with 19 inventory spaces of size 10, there are a total of 6.41 * 10^{25} states. Hence, the number of equations in the model would be close to the number of molecules in 2,300 liters of gas at sea level!

(c) Simulation Models

When analytical models become too complex, an alternative is to use simulation models. Simulation models circumvent the complexity of analytical models because they do not deal with each possible state of the system. Instead, a simulation recreates the probabilistic events which lead to the occurrence of the different states. Statistical properties of the system are acquired by recording the model state transitions as they occur in simulated time. Consequently, while the analytical approach tends to be complex but yields exact solutions relatively rapidly, simulation models tend to be simpler but slower and yield approximate solutions. The accuracy of these approximate solutions is determined by the number of times and the amount of time the simulation is run. A description of a simulation algorithm is given in the following section.

4. Discrete Event Simulation

In the broadest sense, a simulation can be thought of as managing the movement of discrete units within a system as they compete for finite capacity resources.

4.1 Simulation Logic, Entities, Events, and Resources

A simulation model is made up of interconnected modules which form the simulation logic. These modules can represent a variety of actions and objects such as: resources, user defined logic to control the flow of entities, and variable assignments.

The discrete units which move in the simulation are referred to as entities. Entities instigate and respond to events. An event is any change in the state of the manufacturing system. For example, an entity arriving at an idle workstation causes the state of that workstation to change from the idle state to the busy state. Similarly, given that the state of a queue is characterized by the number of entities it contains, an entity arriving in a queue causes the queue state to change from n entities to n+1 entities.

Entities come in two forms: Physical and non-physical entities. Physical entities represent actual physical entities such as steel coils. These physical entities move through the simulation logic causing events to occur. However, non-physical entities have no physical counterpart. They are created either by the user or by the simulation software to manage certain types of events. For example, a simulation software might model machine failures by creating an internal entity which, until a certain elapsed time is reached, causes the state of the machine resource to change to the failed state. Similarly, a user might use internal entities in the simulation model to activate certain events at prescribed times.

Entities instigate events by moving through resources. Resources are stationary components of a simulation which provide services. Examples of resources are machines, queues, and transportation vehicles. Resources are usually capacity limited. For example, machines may process only one steel coil at a time, or a queue may contain no more than 10 coils. Therefore, in competing for resources, entities can seize resources and cause other entities to wait in queues.

The management of the flow of entities competing for resources and the management of events is usually done using discrete event simulation algorithms.

4.2 Discrete Event Simulation

A discrete event simulation is one in which the state of a system changes only at discrete points in simulated time. An advantage of discrete event simulation algorithms is that simulated time can jump from event time to event time rather than changing in fixed increments. However, in building a model in a discrete environment, care must be taken to prioritize the order of events occurring at identical event times.

(a) Components of a Discrete Event Simulation Model

Using the terminology of Law and Kelton [7], a discrete event simulation model is typically made up of the following components:

1. System State: the collection of state variables necessary to describe the system at a particular time.
2. Simulation Clock: a variable giving the current value of simulated time.
3. Event List: a list containing the next time when each type of event will occur.
4. Statistical Counters: variables used for storing statistical information about system performance.
5. Timing Routine: an algorithm that determines the next event from the event list and then advances the simulation clock to the time when that event is to occur.
6. Event Routine: an algorithm which updates the system state when a particular type of event occurs.
7. Report Generator: a subroutine which computes estimates (from the statistical counters) of the desired measures of performance and prints reports when the simulation ends.
8. Main Program: a subprogram which calls the timing routing to determine the next event and then transfers control to the corresponding event routine to update the system state appropriately.

(b) Execution of a Discrete Event Simulation Model

Within a simulation run, entities are always in one of five states: active, ready, time delayed, condition delayed, or dormant state. At any given time in the simulation, only one entity can be in the active state. The active entity progresses through the simulation logic and remains in the active state until it encounters a delay. While an active entity is progressing through the simulation logic, all other entities which are scheduled to move during the given event time are in the ready state. All entities in the ready state wait one-by-one to become the active entity. The time delayed state is assigned to entities waiting for a future simulated time to be reached before they can reenter the ready state. Similarly, the condition delayed state is assigned to entities waiting for some condition to occur before they can return to the ready state. Finally, the dormant state is assigned to entities waiting for a specific user defined action to occur before they can return to the ready state.

At the beginning of any event time, the set of ready entities form the current event list. Entities in the time delayed state form the future event list. Entities in the condition delayed state form the delay list. Entities in the dormant state form the user-managed list.

At any given event time, the simulation goes through the current event list and one-by-one transfers the ready state entities to the active state. This process continues until the current event list is empty, i.e. until all formerly ready state entities have been sent to either the future event list, delay list, or user-managed list. Once the current event list is empty, the simulation checks the delay, and user-managed lists to determine whether any entities in these lists are eligible to move to the current event list. Once the current event list is again empty, all possible events for that event time have been executed, and the simulation activates the timing routine to move to the next event time, and the whole process is repeated.

Because of the occurrence of random events in a simulation, all measures produced by the simulation are random variables. In order to produce confidence intervals for the mean of these measures, several replications of the simulation are necessary. A replication of a simulation is a run of the simulation logic for a certain amount of time under a given set of circumstances and a given random number generating seed. Confidence intervals for the measures of interest can therefore be constructed by running several replications of the simulation, holding all parameters constant and only changing the random number generating seed (for more information on the generation of random numbers, see 'linear congruential generator' in the Definitions section).

5. Methodology

The construction of a simulation model is a five step process. These steps are described in sections 5.1 through 5.5. The remaining sections 5.6 through 5.9 present additional issues on building a simulation model.

5.1 Step 1: Definition of the Objectives of the Simulation Model

The primary objective in building a simulation in the context of this project is to show that it is possible to create models which can accurately capture the impact of product mix and campaigning on processing time, setup time and on the occurrence of setups. Hence, a significant amount of effort is put into understanding how different products request different settings in process parameters, and how these different settings in process parameters and product geometries impact on campaigning, on processing time and on the occurrence of setups.

5.2 Step 2: Simulation of Time to Fail and Time to Repair

(a) Definitions

Within the databases of the company, the word 'delay' has different meanings. For example, the delay codes that exist for a specific facility include delays that are expected scheduled delays (i.e. scheduled maintenance), unanticipated delays and setup times which occur as a result of the product mix going through the facility.

Because of the ambiguity that exists in the definition of the delay codes, care must be taken to identify the category of the delay code (scheduled maintenance, unanticipated delays, and setup times) and any redundancy with other delay codes. An example of this redundancy on anneal and pickle lines is delay code 514 (Change Ni to Cr) and 515 (Change Cr to Ni) which are redundant expressions of delay codes 106 (Temperature Change) and 373 (Acid Change).

(b) Time to Fail and Time to Repair

The time to fail (TTF) is defined as the amount time before an unanticipated failure occurs. The time to repair (TTR) is the amount of time it takes to repair a machine once it has failed as a result of an unanticipated failure. The time to fail and the time to repair are extracted from the 2000 Character Feedback Records (described in section 5.6). A distribution of these quantities can be generated to obtain the distribution of the failure and repair times.

The time to fail is found by summing all consecutive production minutes occurring between unanticipated delay records. Hence, time to fail is expressed in units of production time (i.e. not in units of simulated time). This approach is chosen since it is unrealistic to have machines fail when they are not being used. In calculating time to fail, two assumptions are made. First, it is assumed that the occurrence of unanticipated delays is independent of the frequency of setups at specific facilities. It may be argued that the time to failure should decrease as the number of setups increases. Secondly, the distribution of the time to fail is assumed to be independent of the frequency of scheduled maintenances. While a time based approach is used for computing the time to fail, the occurrence of failures may depend on other variables. For example, the occurrence of backup roll changes on a Sendzimir mill may be more accurately modeled as a function of the total distance of rolled steel. If this is the case, it may be more appropriate to express the time to fail using a count based approach.

The time to repair is found by summing all consecutive delay minutes occurring during the unanticipated delay. Currently, time to repair is expressed in simulation time units. This means that when a failure occurs, it is assumed that a repair resource is available during every subsequent simulated minute until the repair is completed. More complex models can be used. For example, when a repair occurs, the simulation can request a repair resource which may be capacity limited. Then, the time to repair is tallied only during the time that the repair resource is available.

5.3 Step 3: Simulation of Production Time

(a) Relationship between Handling Time, Contact Time, and Production Time

Within the plant studied in this project, steel is always in the form of coils. Hence, the processing facilities, with the exception of the bundling facility, always have at least one payoff reel and one winding reel. On the basis of this mechanical characteristic, the following quantities are defined.

Handling time is defined as the time needed to prepare a coil for processing. Typically, it is the time needed to move the coil from the inventory location and place it on the payoff reel of the facility and the time needed to remove the coil from the winding reel and to weigh it. Contact time is defined as the difference between 'contact-on' and 'contact-off' where 'contact-on' is the time at which the coil comes into contact with the winding reel and 'contact-off' is the time at which the coil is fully wound on the winding reel. Handling time and contact time are not recorded per se in the 2000 character feedback records (see section 5.6). However, a quantity named 'Production Minutes' is recorded. For cost accounting reasons, the 'Production minutes' of a coil, which we also refer to as production time, is defined as the difference between 'time-off' and 'time-on', where 'time-on' is set equal to the 'time-off' of the previous coil and where 'time-off' is recorded after the coil has been removed from the winding reel and weighed. This recording method causes the relationship between handling time, contact time and production time to depend on whether the feed into a facility is continuous or discontinuous.

For a facility with discontinuous feed such as a Sendzimir mill (the mill must be stopped before processing of the next coil can begin), the occurrence of times 'time-on', 'time-off', 'contact-on', and 'contact-off' are depicted for two consecutive coils in Figure 3. As shown in Figure 3, 'contact-off' is inferior to the 'time-off' by an amount Δt because 'contact-off' is recorded when the coil is completely wound on the winding reel and 'time-off' is recorded when the coil is off the winding reel and weighed. For the next coil, 'contact-on' must be greater or equal to 'time-on' by an amount Δt' because the next coil must wait for the previous coil to be removed before its processing can begin and 'time-on' of the next coil is by design equal to 'time-off' of the previous coil. Consequently, there is a nontrivial relationship between production time (i.e. 'time-off' – 'time-on'), contact time (i.e. 'contact-off' – 'contact-on') and handling time (i.e. Δt + Δt').

On the other hand, for a facility with continuous feed, such as anneal and pickle lines, production time is equal to contact time. As shown in Figure 3, the 'contact-off' time is inferior to the 'time-off', by an amount Δt, because 'contact-off' is recorded when the coil is completely wound on the winding reel and 'time-off' is recorded when the coil is off the winding reel and weighed. For the next coil, 'contact-on' is inferior to 'time-on' by an amount Δt because the processing of the next coil begins at the same time as 'contact-off' of the previous coil (this is what characterize a continuous process), and 'time-on' of the next coil is by design equal to 'time-off' of the previous coil. Since the time Δt always originates from the same underlying process of removing a coil from a winding reel and weighing it, it is reasonable to assume that the interval of time Δt is relatively constant. Thus, under this assumption, production time (i.e. 'time-off' – 'time-on') and contact time (i.e. 'contact-off' – 'contact-on') are approximately equal because contact time and production time are simply shifted by an amount Δt.

(b) Model for Production Time for Facilities with Continuous Feed

For facilities with continuous feed, for which the contact time and production time are equal, the model for production time is of the form

$$\textit{production time} = f(\theta) + E[\hat{e}]$$

where f() is the function which describes the relationship between the set of variables θ needed to calculate the contact time, and E[ê] is the expected value of the distribution of the error term given by

$$e_i = \textit{'production time'}_i - f(\theta_i)$$

where i is an index over all coils. Including the mean of the error term in the model for the production time gives the model the desirable property of being an unbiased estimator for the actual production time: on average the difference between contact time and production time is zero.

(c) Model for Production Time for Facilities with Discontinuous Feed

For facilities with discontinuous feed, the relationship between contact time and production time depends on the handling time. Since it is reasonable to assume that handling time cannot easily be modeled on the basis of physical principles, it can be treated as a random variable. Under these circumstances, the relationship between production time, contact time, and handling time is assumed to be of the following form:

$$\textit{production time} = f(\theta) + \hat{H}$$

where f() is the function which describes the relationship between the set of variables θ needed to calculate the contact time, and H is the handling time modeled as a random variable whose distribution is the distribution of the differences 'production time'$_i$ – $f(\theta_i)$.

(d) Validation of Model for Production Time

The accuracy of the production time models for facilities with continuous feed is characterized by the error term whose distribution is the distribution of the differences (actual production time – predicted production time). By design, the mean of this error term is zero, so its standard deviation measures the accuracy of the model. It was found that models with accuracy greater than 80% are satisfactory simply because the error averages to zero during the simulation runs.

Assessing the accuracy of the production time model for facilities with discontinuous feed is not trivial because it is not possible to distinguish the handling time from the error term. In fact this distinction is only possible if some production data is recorded specifically on handling time or contact time.

Since one of the objectives for the simulation models is to capture the impact of product mix on production time, a test is performed to determine how well predicted production time moves with actual production time. This is done by plotting predicted production time and actual production time for a large number of coils. This visual test allows to qualitatively determine the level of correlation between predicted and actual production time.

5.4 Step 4: Model for the Occurrence and Duration of Setups

A model for the occurrence of setups is constructed on the basis of setup rules for the facilities. The accuracy of the rules in predicting the need for setups is determined by comparing the predictions of the model and the actual occurrence of setups in terms of the fraction of false positives (the model predicts a setup when no setup occurs), and false negatives (the model predicts no setup when a setup occurs) generated by the model.

The construction of a model for the duration of setups begins with grouping setup types on the basis of the process parameters they impact (e.g. temperature change, acid change). Then, if there are physical reasons why the setup time might depend on process parameters (e.g. line speed), a regression analysis is performed to test the strength of this relationship. If the regression is significant, then the regression equation is used and the distribution of the residuals is included in the model to capture the variation. Otherwise, if the regression is not significant, then the duration of the setup times is assumed to originate from an underlying distribution with constant mean. The expression for this underlying distribution is found using the 'best fit' algorithm provided with the simulation software.

5.5 Step 5: Verification and Validation Analysis

The verification and validation of the simulation is done at all the steps in the construction of the model. Although time consuming, there are several justifications for this approach. First, the process of verifying and validating a simulation model as a whole is a difficult task. One approach is to subject the model to a set of inputs, with the intent of recreating a set of historical circumstances, and to compare the output with actual measures. However, this approach, which involves holding constant a number of quantities and forcing certain events to occur, can be difficult because it goes against the very purpose of building a simulation: namely to understand the impact of stochastic events on a process. Furthermore, debugging a simulation model as a whole can be a daunting task because of the large number of components from which a bug can originate. In light of these observations, significant effort is put into designing the simulation in separate modules, such as setup logic, contact time logic, campaigning logic, so that each module can be individually verified and validated.

Since Visual Basic® for Applications (VBA) is integrated both in the Systems Modeling® Arena simulation software and Microsoft® Excel, models can easily be transferred between Excel and Arena. Because Excel provides an environment in which parameters can easily be controlled, programs destined to be used in the simulation were written using VBA in the context of Microsoft® Excel and then transferred to Arena with little or no adjustments necessary. As an example of this process, the VBA code used to model the occurrence of setups on No. 90 Anneal and Pickle Line (henceforth referred to as 90 Line) is tested, in the context of Excel, against the actual records to ascertain the accuracy of the model. Once we are confident that all the setup rules are in the model, and that they are all implemented correctly, the VBA code is transferred, with only minor modifications, from Excel to Arena.

Once the validation process is complete for all the simulation components, the simulation model is tested as a whole to determine whether the simulation logic connecting the components is correct. This is done in two steps. First, the simulation is run in a stepwise fashion (i.e. pausing between each event time) to make sure that the simulation is managing events as it was instructed. Secondly, the simulation is subject to a set of inputs to reproduce a set of historical circumstances and the output is compared with actual measures. More specifically, for the simulation model of the anneal and pickle lines, entities are assigned attributes (weight, gauge, width, deviation from due date) according to the historical distribution of these quantities. Furthermore, the entities are released into the model such that the fraction of each order type, and the average campaign size for each order type is approximately equal to historical values of these quantities. The fraction of time spent on setups relative to the total production time is then calculated and compared to the historical value. The number 'fraction of time spent on setups relative to total production time' is a good validation criteria since in order for this measure to agree with the actual value, the duration and occurrence of setups, the campaigning logic and the production time must all be accurately modeled in the simulation logic.

5.6 Extracting Information from the 2000 Character Feedback Records

The main source of information for building the simulation models is the 2000 Character Feedback records. These files contain six to ten months of production and delay records and usually have more than a quarter of a million cells of data (~10,000 rows by ~25 columns). These file show by date and turn, the time-on and time-off of a coil on the facility. Coil characteristics (grade, weight, width, and gauge) and process parameters (temperature, process code, process cycle, etc.) are also recorded. The time-on and time-off fields are also used to record the occurrence of setups and delays.

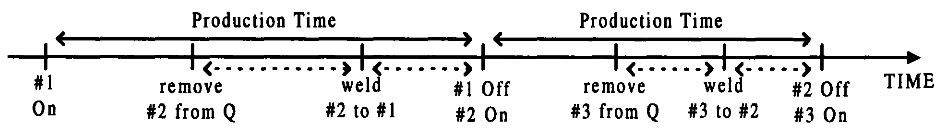
In order to extract information from these large amounts of data, programs and functions are created using VBA to read the data and extract desired measures. As examples, programs are written to extract the time between unexpected failures or the time to repair. Programs are also written to extract the data used for generating distributions of production time by grade or by process cycle.

This approach for extracting information has several significant advantages. First, since it is based on programming, the only constraint on the measures that can be extracted is the data itself. Secondly, measures that are expected to vary over time can easily be re-extracted by running the appropriate programs against a new set of production records.

5.7 Accounting for Time

Because of the vast array of events (in the simulation sense) that occur in the manufacturing processes, it is not always clear which events to or not to include in the simulation model. To address this issue, the construction of a simulation model should be thought of as a process of accounting for the occurrence of the events that take up time. Furthermore, a basic rule is that a simulation model must account for all the minutes that occur in the real manufacturing process. Thus, as long as this requirement is met, all events that overlap in time with the events that are modeled in the simulation logic can be ignored.

For example, consider a coil that is scheduled to be processed at an anneal and pickle line. This coil is subject to the events shown on the time line below: remove coil from queue ('remove #2 from Q'), weld coil to coil currently being processed ('weld #2 to #1'), begin processing coil ('#2 On'), finish processing coil ('#2 Off').



The question is which of these events should be included in the simulation model? Given the rule stated above, this question can be addressed by determining which events allow to describe the progression of time in the simplest way and without gaps. From the time line above, it is apparent that the occurrence and duration of the events 'remove coil from Q' and 'weld coil' overlap with the processing of the coils ("Production Time"). Hence, including a model solely for the production time in the simulation will satisfy the rule.

Since the objective of a simulation is to account for time, analyses are performed to quantify the significance of products or categories of products (such as process cycle or grade) on the basis of their frequency of occurrence in terms of production time. Eliminating all but the most significant of these products or product categories allows to make significant simplifications to the simulation models.

5.8 The Human Component in Building a Simulation Model

Building simulation models of manufacturing facilities obviously requires a thorough understanding of the manufacturing processes. This expertise can usually be routed to a few individuals close to the facilities. My experience has been that these individuals usually have a very good qualitative understanding but may not necessarily have very good quantitative understanding of the processes they manage. This is simply because operators are usually expected to deal with problems on a day to day basis, and are rarely given the opportunity to stand back and perform more general quantitative analyses.

Thus, in order to ascertain the accuracy of modeling decisions based on the qualitative expertise of the operators of the facilities, I found it very useful to treat any statement about the facility as an hypothesis and then check whether or not that hypothesis was supported by the measures extracted from the production records. This approach was found to be very robust in finding errors or missing pieces of information which might otherwise have been difficult to identify further down in the modeling process.

6. Annealing, Pickling, and Cold Rolling Processes

Typically, annealing, pickling, and cold rolling are adjacent operations. The interposition of annealing operations after the severe work hardening imparted to the metal during a cold rolling operation makes it possible to deform most metals to a very great extent.

6.1 The Anneal and Pickle Process

(a) Anneal and Pickle Lines

Annealing is a heat treating process designed to impart softness and ductility to a hardened or cold worked steel. The steel coil is heated to a designated temperature for a sufficient amount of time and then cooled. In physical terms, annealing recrystallizes the grain structure of steel by allowing new bonds to be formed at the high temperature. Pickling is an immersion process in which thick oxide scale, oil, and corrosion on metal surfaces are loosened and dissolved in diluted acid.

Because of the scaling that is produced during the annealing process, annealing and pickling are joint operations. For greater efficiency, the feed into the anneal and pickle line is made continuous by welding coils together. Looper cars at the entry end and exit end of the line allow to maintain the line running while coils are being welded together at the entry end or separated from one another at the exit end (see Figure 4). The speed of the line is determined by the gauge and the processing requested by the coil passing through the furnace. The relationship between these quantities is

$$\text{Line Speed (ft/min)} = \frac{\text{Furnace Length (ft)}}{\text{Gauge (in)} * \text{MPI (min/in)}}$$

where MPI ("Minutes per Inch of Thickness") is given by the processing recipe.

Because successive coils may require different settings of the process parameters (furnace temperature, acid concentrations and line speed), stringers (scrap coils) may be used to allow time for the change in process parameters to occur without stopping the anneal and pickle line.

(b) Campaigning on Anneal and Pickle Lines

To minimize the occurrence of setups on anneal and pickle lines, jobs are grouped into campaigns. Campaigns are created on the basis of the process cycle requested by the coil and the pickle group to which the grade of the coil belongs. A process cycle refers to a unique set of temperature settings, and pressure settings in the furnaces and a unique set of line speed settings. A pickle group refers to a unique set of acid concentrations and acid temperatures on the pickle line. In the two anneal and pickle lines studied in this project, changes in pickle groups always require setups because of the time needed to drain pickle tubes. However, changes in process cycles may not always require a setup if the difference in temperature between the two cycles is inferior to some limit. As will be seen for No. 91 Anneal and Pickle Line (91 Line), from a simulation stand point, it is useful to create a nomenclature based on process cycle and pickle group combinations so that these settings refer to unique combinations of furnace temperatures and acid concentrations. In doing so the simulation logic can be greatly simplified.

Within a campaign, namely within a process cycle / pickle group combination, the minimization of setups imposes an order in which the coils are released for processing. For example, for No. 90 Anneal and Pickle Line (90 Line), coils are released such that the change in gauge in between coils is minimized. Similarly, for 91 Line, coils are released such that the change in cross section from coil to coil is minimized.

(c) Contact Time on Anneal and Pickle Lines

As described in section 5.3.a, because of the continuous nature of the annealing and pickling process, the recorded production time is equal to the contact time shifted in time by an amount equal to the handling time. Furthermore, as described in section 5.7, from a simulation stand point, this means that it is not necessary to construct a separate model for handling time since all production minutes can be accounted for with contact time.

The time needed to process a coil on an anneal and pickle line is a function of coil length and line speed. As shown below, because the speed of the line is determined by the coil going through the furnace, the processing time of the coil depends on two speeds: the speed requested by the coil in question and the speed requested by the coil coming on the line. Thus, the accuracy to which process time can be calculated depends on our knowledge of the distances that the coil travels at the speeds requested by the two coils.

Consider a situation in which three successive coils C_1, C_2, and C_3 request different line speeds S_1, S_2, and S_3 respectively. As shown in Figure 4, let d_1 be the distance along the path of the coil from the pay off reel to the exit end of the furnace, let d_2 be the path from the exit of the furnace to the winding reel. Let L be the length of the second coil. Assume that S_1, S_2, and S_3 are sufficiently close to one another so that no stringers are necessary. Assume that coil C_1 has just entered the furnace. Coil C_1 passes through the line at speed S_1 for a distance d_1 until it exits the furnace. Once coil C_1 exits the furnace, the speed of the line is automatically ramped up or down to speed S_2 (a change in speed occurs in less than a minute). Thus, coil C_2 passes through the line at speed S_2 for a distance d_2. The moment coil C_2 comes into contact with the winding reel, contact time begins to be recorded. Since $L - d_2$ feet of the coil C_2 remain to pass in the furnace, the coil passes through the line at speed S_2 for a distance $L - d_2$. Once coil C_2 is out of the furnace, coil C_3 is in the furnace, so coil C_2 ends its pass through the line at speed S_3 for a distance d_2. Thus, the time to process coil C_2 is

$$T = \frac{L - d_2}{S_2} + \frac{d_2}{S_3}.$$

The fraction of time spent at either speed therefore depends both on distance d_2, which varies with the position of the looper car, and on the length L of the coil. No information is recorded on the position of the looper car when a coil goes through the line. Because of the looper cars at both ends of the anneal line, the distances d_1 and d_2 may range from approximately 200 feet to 1000 feet. On average, these two distances are around 400 ft. The average length of a coil is 1000 feet. Thus, approximately 60 % of the coil goes through the line at the speed requested by the coil and 40% goes through the line at the speed requested by the next incoming coil. Finally, if coil C_2 is a stringer then, because the line speed requested by the stringer and the line speed requested by the next incoming coil are equal, the contact time is simply L / S_2.

6.2 The Cold Rolling Process

(a) Description of the Cold Rolling Process

Rolling is the process of plastically deforming a metal by passing it between rolls. In conventional cold rolling, the main objective is to decrease the thickness of the metal by successive passes. The gap between the rolls is reduced after each pass. Typically, as the metal passes through the rolls it is reduced to a thinner section, elongated proportionally in length, but spread laterally only a small amount. Cold rolling is used to produce metal sheet or strip with superior surface finish and superior dimensional tolerances than are possible with hot rolling.

The forces involved in rolling can reach many millions of pounds. A very rigid structure is therefore needed and very large motors are required to provide the necessary power. In the design of a rolling mill, smaller diameter rolls can be used to reduce the power requirements. However, the smaller the diameter of the work rolls, the lower the strength and rigidity. Thus, when small work rolls are used, additional support is introduced by adding larger diameter backup rolls. The Sendzimir mill is one such design in which the small diameter roll in contact with the metal is surrounded by a set of four backup rolls, as shown in Figure 5.

The feed into the Sendzimir mill is discontinuous. A coil coming on the mill must wait for the coil currently on the mill to be removed before its processing can begin.

(b) Campaigning on a Sendzimir Mill

Because changes in width and finish require different work rolls to be used, campaigns on a Sendzimir mill are based on the width of coils and on the required finish.

(c) Contact Time on a Sendzimir Mill

The processing time on a Sendzimir mill depends on the length of the coil and the speed of the motor during each pass. Because hardness, tensile strength and yield strength increase with the amount of gauge reduction, the percentage gauge reduction decreases for each successive pass. Thus, the length of the coil after each pass changes in a nontrivial way.

The rolling speed varies between passes. Typically, because of the movement of the workpiece surface layers relative to the interior, the speed per pass increases and the percentage gauge reduction decreases at each pass. The reason for this movement is that the steel must be accelerated while moving through the roles in order to keep the volume rate of flow constant. For example, during a 50% reduction in gauge, the work leaves the rolls at approximately twice the speed of the entering work. Since the gauge reduction is maximum for the first pass, the movement of the workpiece surface layers is most dramatic and lower speeds are used to avoid damaging the coil. Furthermore, the lowest percentage reduction is taken in the last pass to permit better control of gauge and surface finish.

7. Simulation Model for No. 90 Anneal and Pickle Line

7.1 Campaign Groups Included in Model

As discussed in Section 6.1.b, campaign groups on 90 Line are based on the process cycles that coils are scheduled to undergo. A frequency distribution of the occurrence of these process cycles by number of instances and by time over the period 01/01/97 – 07/31/97 is shown in Figure 6. Process 501 is the most common (73% of the production time). To minimize the computation time in the simulation without jeopardizing accuracy, six of the process cycles that occur on 90 Line are included in the model. These six process cycles account for more than 90% of the total production time. These process cycles are:

Process Cycle Code	Production Minutes (%)	Instances (%)	Description
501	73.4	69.9	Hot Roll Anneal, All Cr-Ni Grades (Except T304 DA)
402	5.7	9.1	Hot Roll Anneal, Grades: 406, 410S, 419, 466, 467
430	3.7	3.8	Hot Roll Anneal, Grade: 430 (Box Annealed)
388	3.7	3.6	Final Anneal, Grade: 409
401	1.9	2.9	Hot Roll Anneal, Grades: 430 (Not Boxed Annealed), 436S, 437, 441, 443, 444, 468
367	2.2	2.2	Hot Roll Anneal, Grade: 437

Table 1: 90 Line: Process Cycles Included in Simulation Model

7.2 Time to Fail and Time to Repair

Figure 7 shows the fraction of minutes and fraction of instances of each delay code that occurred at 90 Line over a 6 month period. The following delay codes are treated as unscheduled downtimes and are used to determine the time between failure distribution for 90 Line.

Delay Code	Delay Description
001	Mechanical
002	Electrical
003	Other Stoppage
121	Wheel Delay
122	Welder Delay
123	Broken Coil / Weld
172	Broken Strip and / or Weld

Table 2: 90 Line: Delay Codes for Failure Distribution

In addition to these delays, delay 006 ('Normal Startup') and 112 ('Running Tail Stock') are included in the calculation of the time to repair. The expressions for the time to fail and time to repair distributions are shown below.

	Distribution (Minutes)	Figure
Time to Fail	9.610 * BETA(0.449, 1.55)	Figure 8
Time to Repair	WEIB(69.3, 0.641)	Figure 8

Table 3: 90 Line: Time to Fail and Time to Repair Distribution

The time to repair is expressed in simulation time minutes. The time to fail is expressed in production minutes.

7.3 Model for the Occurrence and Duration of Setups

(a) Model for Occurrence of Setups

The setups included in the simulation logic are 106 ("Gauge Change"), 109 ("Temperature Change"), 112 ("Running Tail Stock"), 373 ("Acid Change"), 514 ("Change NI to CR"), and 515 ("Change from CR to NI"). The setups 011 ("Width Change") and 512 ("Change A&P to Repickle") occurred one and three times respectively during the period 1/1/97 through 7/31/97. Because of the rarity of these two setups, they have not been included in the model.

The following two rules determine when stringers are needed for temperature changes or for gauge changes. For confidentiality reasons, the exact formulation of these rules is not given.

- Rule 1: A temperature change requires a stringer whenever a significant temperature change occurs. This rule results from the rate at which the temperature of the furnace can be changed. If a stringer is not then the incoming coil may be over-annealed (for a decrease in temperature) or under-annealed (for an increase in temperature).
- Rule 2: A gauge change requires a stringer whenever the line speed changes by more than a certain percentage. This rule results from the rate at which the speed of the line can be changed. As in rule 1, failure to use a stringer will cause the incoming coil to be either under-annealed (for a decrease in line speed) or over-annealed (for an increase in line speed).

Application of rule 1, results in grouping the process cycles in the following four temperature categories. The temperatures are for the three temperature zones of the 90 Line furnace.

Category	Temperature (°F)	Cycle Code
1	1400, 1400, 1400	402, 430, 401
2	1800, 1825, 1800	388
3	1925, 1875, 1800	367
4	1900, 2190, 2240	501

Table 4: 90 Line: Temperature Settings by Process Cycle

An acid change is required whenever a change is made from low hydrofluoric acid (HF) concentration to high HF concentration process cycles.

Category 1 High HF	Category 2 Low HF
501	402
430	388
401	
367	

<u>Table 5</u>: 90 Line: Acid Categories by Process Cycle

Thus, any movement from an acid or temperature category to another requires a setup.

The accuracy of the model for the occurrence of stringers is measured by applying these setup rules to the 7 months of production records and calculating the occurrence of false positives (model predicts a stringer when no stringer is used), false negatives (model predicts no stringer when a stringer is used). The table below summarizes the results:

		Actual	
		Stringer	No Stringer
Model	Stringer	94.4%	4.2%
	No Stringer	5.6%	95.8%

<u>Table 6</u>: 90 Line: Validation of Model for the Occurrence of Setups

The following section describes the model for the duration of the setups.

<u>(b) Model for the Duration of Setups</u>

While the nomenclature for delay codes separates delays into 6 categories (gauge change, temperature change, acid change, change Ni to Cr, change Cr to Ni, other categories exist but are seldom used) the underlying process behind these delays is passing a scrap coil (a stringer) through the anneal and pickle line to allow the change in process parameters to occur. Thus, the duration of these delays may be a function of the stringer length and the line speed. While the length of the stringer might be chosen to accommodate the time needed to change the process parameters, discussions with people who work around 90 Line suggest that there are no strict rules behind the selection and availability of stringers. To test this hypothesis, a regression of setup time versus inverse of line speed was performed. A weak correlation coefficient between these two variables would suggest that stringer length is chosen according to line speed so that a certain setup time is achieved. On the other hand, a significant correlation between these two variables would suggest that the stringer length is not necessarily taken into account in the selection of stringers and that line speed does influence the duration of the setup.

The model for the duration of setups is

$$T_i = \alpha_0 + \alpha_1 \cdot \frac{1}{V_i} + \varepsilon_i \qquad i=1,2,\ldots,n$$

where T is the duration of the setup (minutes), V is the final line speed (feet / minute), ε is the error term and i the index ranging over all data points. The final line speed is chosen as the regressor because the speed at which the stringer goes through the anneal and pickle line is the same as the speed requested by the next incoming coil (see section 6.1.c).

The data in this regression includes all delay records with delay code "106" (Gauge Change), "109" (Temperature Change), "373" (Acid Change), "514" (Change Ni to Cr), "515" (Change Cr to Ni) which did not occur next to unexpected delays. The reason for imposing this restriction is that setup times occurring next to unexpected delays were found to be abnormally long. This may either be due to erroneous recording of time or special circumstances. The regression is shown in Figure 9. The dashed lines are the regression lines for the data corresponding to individual delay codes. The regression line for all the delay codes (i.e. the main regression line) is shown in bold.

Except for delay code 515, the regression lines for the individual delay codes 106, 109, 373, and 514 are all close to the main regression line. This supports pooling the data among all delay codes to perform one main regression. The F-ratio for the main regression line is 183 which is much larger than the critical value F(1%, 1, 339) ~ 6.63. Thus, we conclude that $\alpha_1 > 0$: the main regression is statistically significant. The distribution of the residuals is incorporated in the model to capture the variation in the setup times. The model is:

$$\boxed{\text{Setup Time} = 10.9 + 741.81 \cdot \frac{1}{\text{Final Line Speed}} - 19 + 93 \cdot \text{BETA}(4.26, 16)}$$

where setup time and final line speed are expressed in minutes and feet per minute, respectively. There is no clear interpretation to the values of the coefficients α_0 and α_1 other than that they have dimensions of time and length respectively. Under the assumption that stringers are always chosen at random regardless of the line speed, α_1 is the average length of a stringer and α_0 should be 0 because as the line speed goes to infinity, the time needed for the stringer to pass through the line goes to zero. Conversely, under the assumption that stringers are always chosen such that, for any given line speed, the time for the stringer to pass through the line is equal to time needed for the change in process parameters, then there should be no correlation between line speed and setup time. Under this assumption, α_1 should be 0 and α_0 should tend to the average setup time. Since in the regression, neither α_0 nor α_1 are zero, the regression equation represents a superposition of these two assumptions.

The setup time and the final line speed are expressed in simulation time minutes and feet per minute, respectively. In the simulation, the absolute value of this expression is used to insure that the random component never causes the expression to yield a negative value for setup time.

7.4 Model for Production Time

As discussed in section 5.3.a, since 90 Line has a continuous feed, the contact time is equal to the production time. Consequently from a simulation stand point, it is not necessary to construct a separate model for handling time since all production minutes can be accounted for with contact time. As discussed in section 6.1.c, the contact time of a coil on an anneal and pickle line is given by

$$T = \frac{L-d}{S} + \frac{d}{S_n}$$

where L is the length of the coil, d is the distance from the exit end of the furnace to the winding reel, S is the speed requested by the coil in question and S_n is the speed requested by the next incoming coil. To simplify the simulation, it was assumed that S and S_n are sufficiently close so that the contact time can be simplified to $T = L / S$.

The contact time is calculated by computing the length and the speed of the line requested by the coil. Given the grade, gauge and the process cycle that a coil is scheduled to undergo, it is possible to calculate the speed of the line from the set of 'Standard Annealing Instructions'. If the 'Standard Annealing Instruction' for a specific process cycle is based on a constant minutes per inch of thickness (mpi), then the line speed is derived from the gauge and the furnace length:

$$\text{Line Speed (ft/min)} = \frac{\text{Furnace Length (ft)}}{\text{Gauge (in)} * \text{MPI (min/in)}}$$

However, if within the same process cycle, the 'Standard Annealing Instruction' is based on varying mpi, then the line speed can be stated as a step function of gauge. Then, calculating the length of the coil,

$$\text{Coil Length (ft)} = \frac{\text{Weight (lb)}}{\text{Gauge (in)} * \text{Width (in)} * \text{Density (lb/in}^3) * 12}$$

and dividing by the line speed, yields the contact time:

$$\text{Contact Time (min)} = \frac{\text{Coil Length (ft)}}{\text{Line Speed (ft/min)}}$$

To quantify the error in the model, the distribution of the error is found by subtracting the predicted contact time from the recorded 'production minutes' (i.e. recorded production time – contact time). It was found that abnormally high error terms result with coils of very low width (<10 in) and very low weight (<6000 lb.). Under these rare conditions, the processing rules used to process these coils may differ from the processing rules found in the 'Standard Annealing Instructions'. Also, abnormally high error terms were found for coils whose processing occurred just before, or just after the occurrence of a delay. This may be due to the way time-on or time-off are recorded under these circumstances. Hence, the distribution of the error term is found by considering only coils whose weight is greater than 6000 lb. and width greater than 10 inches and whose processing did not occur before or after a delay. The best fit distribution to the histogram of the error term is a normal distribution with mean 2.56 and standard deviation 4.28 minutes.

$$\hat{e} \sim Normal(\mu = 2.56, \sigma = 4.28)$$

To remediate the tendency of the model to underestimate production time, a correction term equal to the mean of the error term is added to the expression for contact time:

$$\boxed{\text{Production Time (min)} = \frac{\text{Coil Length (ft)}}{\text{Line Speed (ft/min)}} + 2.56}.$$

Although it is not clear what would cause a 2.56 minute shift in the error term, the following observations may explain the origin of the shift and of the variation.

First, it is possible that the anneal and pickle line is consistently run at speeds slower than those suggested by the 'Standard Annealing Instructions'. The histogram of the difference between the recorded and the theoretical feed rate (i.e. recorded feed rate – theoretical feed rate) was constructed. The mean of the histogram is -0.57 feet per minute (fpm) and the standard deviation is 8.6 fpm. This implies that the recorded actual feed rate is, on average, slightly lower than the theoretical feed rate. This data therefore supports a slight tendency (< 1 minute) for the model to underestimate contact time.

Furthermore, the large standard deviation (8.6 fpm) in the histogram can account for the level of variation in the error term in the expression for the contact time. For example, consider a coil that is 1000 ft long and a line speed of 30 fpm. If the coil is processed at that line speed, the contact time is 33 min. If the line speed is half a standard deviation below 30 fpm (i.e. ~26 fpm) then the contact time increases to 38 minutes: a 6 min (or 18%) increase in contact time.

Thirdly, as described in section 6.1.c, the amount of time that the anneal and pickle line spends at the speed specified in the annealing instructions for a specific coil only applies while the coil is passing through the furnace. Once the coil has gone through the furnace, the line speed is changed to accommodate the next incoming coil. Thus, the processing time of a coil depends both on the speed requested by the coil in question and on the speed requested by the next incoming coil. Finally, variation in the amount of time it takes to remove a coil from the winding reel and to weigh it, will introduce variation into the model.

To ascertain the accuracy of the model for production time on a coil by coil basis, Figure 10 compares the actual production time with the predicted production time for 400 coils. This graph shows that predicted production time and actual production time move together with a very satisfactory degree of accuracy.

7.5 Simulation Logic for No. 90 Anneal & Pickle Line

This section gives a general description of the simulation model for 90 Line.

(a) General Description of the Simulation Logic for No. 90 Anneal and Pickle Line

Because of the campaigning rules that determine the sequence in which coils are removed from the queue, the simulation logic for 90 Line divides the actual physical queue into seven separate queues. The first six of these queues represent the groupings from which campaigns are created. These six queues contain coils that request identical furnace temperatures and identical acid concentrations. Henceforth, these six queues are referred as the '90 Line campaign queues'. The seventh queue contains coils that have been assigned to a campaign for imminent processing. Since the coils contained in this queue are part of a campaign, they are sorted by gauge to minimize the occurrence of setups resulting from gauge changes. Henceforth, the seventh queue is referred to at the '90 Line gauge queue'.

As long as a campaign is being processed (i.e. as long as there are coils in the gauge queue), arriving coils accumulate in the six campaign queues according to the cycle code which the coils are scheduled to undergo. Once the campaign is finished (i.e. once the gauge queue is empty), an algorithm is executed to create a new campaign from one of the six campaign queues. The reader will notice that while process cycle 430 and 401 are in the same temperature category and require the same pickle concentrations, they are not part of the same campaign group. The reason for keeping them separate is because these process cycles request significantly different line speeds. Combining them to form a single campaign group is not optimal since a significant number of setups would occur as a result of speed changes.

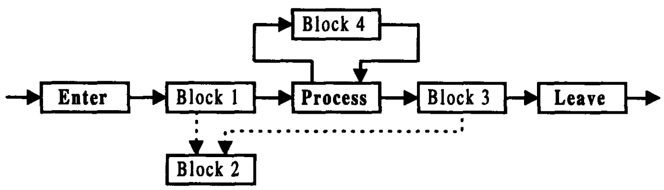
The following campaign logic has been implemented to model the actual creation of campaigns. When a coil arrives at 90 Line, it remains in the campaign queues until the current running campaign is finished. Once the current campaign is finished, the simulation finds the campaign queue containing the coil with the earliest due date among all the campaign queues (let this be queue #1). If this earliest due date is earlier, by more than a user defined number of days, than the earliest due date in the campaign queue from which campaigns are currently being released (i.e. the current queue), then the simulation creates a campaign from queue #1. Otherwise, the simulation creates a campaign from the current campaign queue.

The size of a campaign is determined by requesting all the coils due on the earliest due date in the selected queue. If this yields a campaign smaller than a limit set by the user, then the simulation can also request all coils due on the next earliest due date. This process is repeated until the user defined limit is reached or until all the coils in the queue have been requested. Once the size of the campaign is calculated, all the coils in the chosen campaign queue are sent to the gauge queue to be sorted by gauge. Once the sort is complete, the coils are released one by one for processing.

Each time a coil is selected for processing, an algorithm compares the processing requested by the incoming coil with the processing requested by the previous coil. If a setup is needed, then the incoming coil is delayed for an amount of time equal to the setup time. Subsequently, the coil experiences a delay equal to the calculated production time.

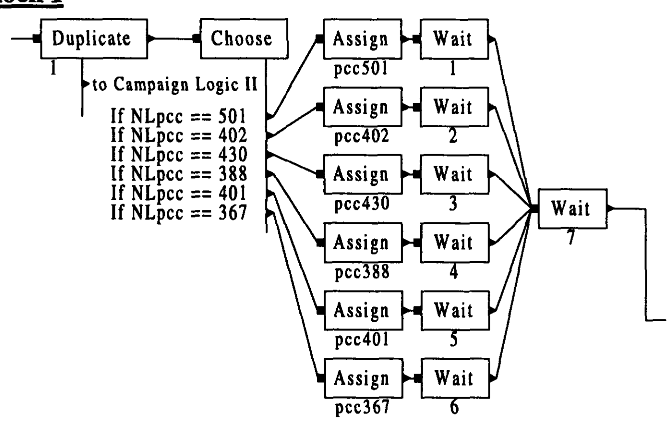
(b) Overall Structure of the Model

The simulation model for 90 Line is shown in Figure 11. The general form of the model is shown below:



The Enter, Process, and Leave modules are respectively the entrance, processing area, and exit of 90 Line. The dotted path in the above diagram represents the path taken by non physical entities. Solid lines represent the routes taken by physical entities. Block 1, 2 ,3 and 4 respectively represent the modules in the "Campaign Logic I" box, in the "Campaign Logic II" box, in the "Campaign Logic III" box, and in the "Setup & Processing Logic" box. Each block is described in the following sections.

(c) Explanation of Block 1



Upon arriving in block 1 (Campaign Logic I), an entity (coil # 1) activates the Duplicate module which causes a new entity (duplicate #1) to be sent to Block 2 (Campaign Logic II). Coil #1 continues to the Choose module. The Choose module routes the coil to one of the Assign modules according to the process cycle which the coil is scheduled to undergo. The Assign module assigns a specific predefined picture to the coil. Finally, the coil enters one of the 6 Wait modules. These six Wait modules are the six campaign queues described in section 7.5.a.

As the name indicates, a coil entering a Wait module must wait until a signal is received to release the coil (using the terminology of section 4.2.b, these entities are in the Dormant state). Because of the Choose module, the first six Wait modules in Block 1 contain coils waiting to undergo identical process cycles. For example, the first Wait module from the top contains all the coils scheduled to undergo process cycle 501. These wait modules are also designed to sort coils by due date. Hence, whenever a signal is received to release coils from one of the 90 Line campaign queues, the coils are released in order of due date.

Upon receipt of a release signal, the coils from one of the campaign queues are transferred to the seventh Wait module. This Wait module is designed to sort the incoming coils by gauge. The purpose of this is to prepare a campaign with the least amount of variation in gauge between successive coils. This Wait module is the gauge queue described in section 7.5.a. The signaling of the campaign queues and the gauge queue to release coils is governed by blocks 2 and 3, which are described in the following section.

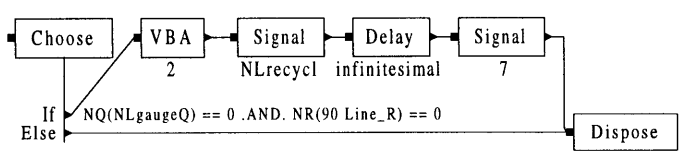
(d) Explanation of Block 2 and Block 3

The purpose of blocks 2 and 3 is to control how many and when coils are sent from the campaign queues to the gauge queue, and when coils are sent from the gauge queue to the process module. A signal to release coils from the campaign queues or from the gauge queue may originate from either Block 2 or Block 3. To prove that two signaling locations are necessary, consider the following two scenarios.

First, consider a situation where only one coil arrives in the model. In order for that coil to reach the Process module, it must initiate its own release signal so that it is released from the campaign queue and then from the gauge queue. Thus, a release mechanism must be incorporated in the model before the coil enters the Wait modules. This is the purpose of Block 2.

Secondly, consider a situation where a campaign is currently running on 90 Line (i.e. coils are present in the gauge queue) and coils are present in the campaign queues and no other coils are scheduled to enter the model. Since coils are present in the campaign queues, these coils must have already sent signals to initiate their own release. However, these release signals were ignored because a campaign was currently being processed. Thus, in order for the coils in the campaign queues to be released, a release mechanism must be incorporated in the model after the Process module. This is the purpose of Block 3.

Description of Block 2 (Campaign Logic II)

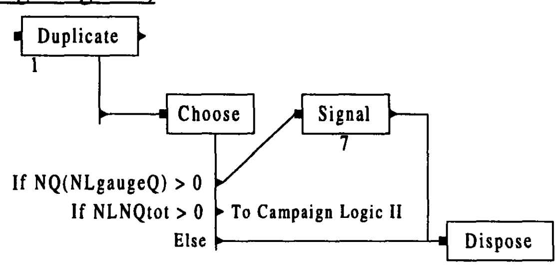


When the coil arrives in Block 1, a duplicate of it is sent to Block 2. This duplicate entity is a non physical entity in that it does not represent an actual steel coil. By design, the duplicate entity waits until the original arriving entity (which led to the creation of the duplicate) reaches a delay, queue, transfer or hold type module before activating the modules along its path. Thus, the physical entity (i.e. the coil) enters its respective campaign queue before the duplicate entity is allowed to proceed through the simulation logic.

Upon entering block 2, the duplicate entity activates the Choose module. If the gauge queue contains coils and if the Process module is processing a part, then the duplicate entity is destroyed because coils should not be released from the campaign queues if a campaign is already being processed. In other words, a duplicate entity is accepted for signaling releases only if both conditions 'the gauge queue is empty' and 'the process module is not processing a coil' are satisfied.

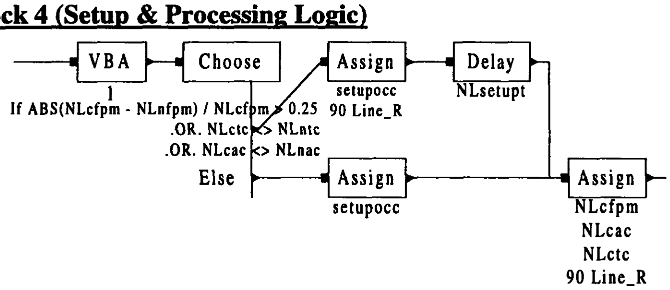
If these two conditions are satisfied, then the duplicate entity is sent to the VBA2 module. The content of this module is described in Appendix 2. Its purpose is to determine from which campaign queue to create the next campaign and to determine the size of that campaign. Once this module is executed, the duplicate entity activates the Signal module to release the coils from the selected campaign queue into the gauge queue. The duplicate entity then activates a Delay module which causes the simulation to wait an infinitesimal amount of time (10^{-9} min) before allowing the duplicate entity to continue forward. Finally, the duplicate entity activates another Signal module to release the first coil in the gauge queue to the Process module. The infinitesimal delay is necessary because without it, the signal to release coils from the chosen campaign queue is synchronized with the signal to release coils from the gauge queue. This causes coils to get released from the campaign queue, but not from the gauge queue. The infinitesimal delay forces the simulation to wait for the coils to get sent to the gauge queue before signaling their release into the processing module.

Description of Block 3 (Campaign Logic III)



When coils exit the Process module, a duplicate entity is sent to Block 3. If the gauge queue contains coils, then the duplicate entity signals the gauge queue to release the next coil from the campaign into the process module. If the gauge queue is empty, and if there are coils in the campaign queues, then the duplicate entity is sent to block 2 to activate the logic responsible for releasing coils from the campaign queues. Finally, if none of these conditions are satisfied, namely if the gauge queue and the campaign queues are empty, then the duplicate entity is ignored and destroyed in the Dispose module.

(e) Description of Block 4 (Setup & Processing Logic)



When a coil is sent from the gauge queue to the Process module, the simulation first sends the coil through the logic in block 4. The coil first activates the VBA1 module. The content of this module is described in Appendix 2. This module is responsible for calculating the amount of time needed to process the incoming coil and calculating the processing states (furnace temperature, pickle group and line speed) requested by the incoming coil. Comparing these new processing states with those requested by the previous coil, the VBA1 module determines whether a setup is necessary. If a setup is necessary, the coil is sent in the upper branch of the Choose module. The Assign module is activated and causes the state of the 90 Line resource to change from the Busy state to the Setup state. This state change allows the simulation to keep track of the fraction of time the Process module spends in the setup state. The coil then activates the Delay module, which causes the setup time to be incurred. The coil activates another Assign module which changes the state of the Process module from the Setup state back to the Busy state. The coil is then sent back to the Process module where a processing delay is incurred. Upon departing, the coil activates the Duplicate module which creates a duplicate entity responsible for initiating the release of a coil from the current campaign, or to initiate the release of a new campaign.

7.6 Accuracy & Validation of the Simulation Logic for No. 90 Anneal & Pickle Line Model

(a) Production Time

The accuracy of the model for production time was discussed in section 7.4. The error term in the model for contact time is distributed normally with mean 0 and standard deviation 4.28 minutes. Given that the average processing time on 90 Line is 35 minutes, this standard deviation corresponds to an error of approximately ± 15%.

(b) Occurrence and Duration of Setup Times

The accuracy of the model for the occurrence of setups was ascertained by calculating the fraction of false positives and false negatives predicted by the model. This was discussed in section 7.3.a.

The accuracy of the model in terms of the duration of setups and in terms of the simulation logic is determined by comparing the fraction of time spent on setups predicted by the simulation model with the historical figure. For the comparison to be meaningful, entities are released into the simulation such that the following quantities are equal to the historical averages:

- Gauge, width, weight: Since there is no significant correlation between cross section and weight, coils arriving into the simulation logic are assigned gauge, width and weight by sampling from the distribution of these quantities over the historical period of interest. The weight distribution is divided into two distributions to represent single and double coils separately. The probability that the weight of a coil is sampled from either of these two distributions is determined by the fraction of single coils (68%) and double coils (32%).

- Deviation from Due Date: Coils are assigned a number representing how many days they are late or early with respect to their arrival date in the 90 Line campaign queues. This number is assigned by sampling from a distribution of the quantity 'deviation from due date' available in the 2000 character feedback records.
- Campaign sizes: The average campaign size for the different campaign groups must be accurately reproduced in the simulation since campaign size obviously has a significant impact on the occurrence of setups. The average campaign size is found by counting, in the production records, the number of consecutive coils belonging to the same campaign group.
- Fraction of coils belonging to each campaign: The fraction of coils belonging to each campaign must be accurately reproduced in the simulation in order to reproduce the frequency of occurrence of the campaigns.

The validation analysis is simplified by ignoring the occurrence of failures or the occurrence of scheduled maintenances. The reason for this simplification is that adjustments can very easily be made within the simulation software so that the occurrence of failures and the repair times coincide with the historical numbers.

The validation experiment is implemented into the simulation by creating six Arrival modules which create coils scheduled to undergo the six process cycles included in the model. The arrival rate of these coils is set so that coils arrive rapidly (one per minute) until each campaign queue contains a number of coils at least equal to the average campaign size for that campaign group. Once a campaign queue contains a number of coils greater than the average campaign size, the arrival rate is decreased to a length of time which is determined by the frequency of occurrence of the process cycle.

As an example of this procedure, consider process cycle 402. The following release logic is used: 'Release coils rapidly into the 402 campaign queue if the number of entities in that queue is inferior to 11. If the 402 campaign queue contains more than 11 coils, then wait n minutes before releasing the next coil into the queue'. The time n is initially set to 1440 minutes (= 1 day). If, after running the simulation, the simulation output shows a frequency of occurrence of more than 10%, then n is increased gradually. This process is repeated until the 'frequency of occurrence' numbers approximately match the historical values for all the process cycles. The average campaign sizes are achieved in the simulation by forcing the simulation, once it has chosen from which campaign group to create the next campaign, to retrieve a number of coils equal to the average campaign size of that campaign group.

Fifty replications of the simulation were run under these conditions. The replications are 100,000 minutes long (approximately 2 months) with a warm-up period of 10,000 minutes. The warm-up period is to allow the simulation to reach steady state. One replication takes approximately 45 seconds on a Intel® Pentium 133 MHz computer. The table below shows the historical averages for the quantities described and summarizes the simulation output using 95% confidence intervals.

	HISTORICAL		SIMULATION			
Campaign Group	Fraction of Coils	Average Campaign Size	Fraction of Coils		Average Campaign Size	
			Lower Limit	Upper Limit	Lower Limit	Upper Limit
501	74%	35	74.0%	74.8%	35.5	35.7
402	10%	11	9.5%	10.1%	11.0	11.0
430	5%	10	4.9%	5.1%	9.1	9.1
388	4%	6	4.1%	4.4%	5.9	6.0
401	5%	7	4.1%	4.3%	6.0	6.2
367	2%	6	3.4%	3.6%	5.8	5.9

Fraction of Time Spent on	Historical	Simulation	
		Lower Limit	Upper Limit
Setups	5%	5.1%	5.2%
Processing	95%	94.9%	94.8%

Table 7: 90 Line: Overall Validation of the Simulation Model

Comparing the '% Occurrence of xxx cycle' and the 'Campaign Size for xxx Cycle' numbers in the above table with the historical numbers shows that the simulation was run in conditions similar to the actual conditions. The simulation model predicts a percentage time spent on setups of 5.15%. The actual percentage of time spent on setups is 5%. The deviation is less than 1%.

While the accuracy of the model is impressive, we must consider this result with caution. Given that 75% of the coils processed in the simulation runs are coils scheduled to undergo process cycle 501, the behavior of the model is sensitive to the exogenous variables which describe how the model should deal with this campaign group. For example, for these runs, the simulation was instructed to request process cycle 501 campaigns of at least 35 coils (equal to the historical average campaign size). If the requested campaign size is decreased to 20 coils, the time spent on setups increases to approximately 7.5%. Similarly, increasing the arrival rate of the coils scheduled to undergo process cycle 501 decreases the time spent on setups. For example, if the arrival rate is such that 85% of the coils processed underwent process cycle 501, and the requested campaign size is 35, the fraction of time spent on setups decreases to 4%.

The simulation logic appears to accurately model the processing time, and the occurrence and the duration of setups. Furthermore, it is important to keep in mind that the model is based on the following exogenous variables: (1) the minimum difference between the earliest due date among all the campaign queues and the earliest due date in the current campaign queue from which campaign are created, (2) the minimum campaign sizes for each campaign group.

8. Simulation Model for No. 91 Anneal and Pickle Line

8.1 Campaign Groups Included in Model

Unlike No. 90 Anneal and Pickle line, a process cycle code in 91 Line does not refer to a unique combination of furnace temperatures, and acid concentrations. For 91 Line, a process cycle refers to a specific set of furnace temperature settings and line speeds, and may be applicable to different grades belonging to different pickle groups. Thus, unlike 90 Line where campaign groups are based solely on cycle codes, 91 Line campaign groups are based both on process cycle and pickle group. For the purposes of building a simulation model, the nomenclature for process cycles was modified by combining the process cycle code and the pickle group. For example, process cycle 511, which is applicable to grades belonging to pickle group 7 and pickle group 9, is divided in the new nomenclature into two separate categories: 511-7 and 511-9.

The distribution of the process cycle / pickle group combinations is shown in Figure 12. The process cycle / pickle group combinations included in the model are: 532-9, 532-7, 319-1, 500-9, 367-5, 511-9, 533-9, 321-1, 534-9, 511-7, 384-2, 444-9, 538-8, 533-7, 444-1, 500-7, 516-9, 383-6. These combinations account for approximately 95% of the total production time on 91 Line.

8.2 Time to Fail and Time to Repair

Figure 13 shows the fraction of total minutes and fraction of total number of instances of each delay code over a 9 month period (1/1/97 – 9/30/97). The following delay codes are treated as unscheduled downtimes and are used to generate the time to fail and the time to repair distributions for 91 Line.

Delay Code	Delay Description
001	Mechanical
002	Electrical
003	Other Stoppage
006	Normal Startup
172	Broken Strip and / or Weld

Table 8: 91 Line: Delay Codes for Failure Distribution

The expressions of time to fail and time to repair distributions are shown below.

	Distribution (Minutes)	Figure
Time to Fail	5 + WEIB(1090, 0.701)	Figure 14
Time to Repair	4 + WEIB(70.4, 0.721)	Figure 14

Table 9: 91 Line: Time to Fail and Time to Repair Distribution

In the simulation logic, the time to repair is expressed in simulation time minutes, the time to fail is expressed in production minutes.

8.3 *Model for Occurrence and Duration of Setups*

(a) Model for the Occurrence of Setups

The delay codes that fall under the category of setups are delay codes 106 ("Gauge Change"), 109 ("Temperature Change"), 373 ("Acid Change"), 380 ("Cross Section Area Chg > 60%"), 512 ("Change A&P to Re-Pickle"), and 513 ("Change Re-Pickle to A&P"). Delay code 011 ("Width Change") is seldom used and is therefore not included in the model.

The occurrence of delay codes 109, 373, 512, 513 is determined using a process cycle transitioning grid (designed by D.E. Schnur and E.L. Hajel). Since only the most common process cycle / pickle group combinations are included in the simulation model, only a portion of this grid is used, as shown in Figure 15. The reader will notice that transitions between process cycles 511, 532, 533, 534 may require a stringer if a change in pickle group occurs. All other transitions, with the exception of transition 321 to 219, require a stringer at least for a temperature change or for an acid change.

The occurrence of delay code 380 is determined by applying the rule which states that a stringer is necessary whenever the cross sections of two consecutive coils differ by more than a given percentage. Finally, the occurrence of delay code 106 is determined by the weldable gauge range rule which states that the gauges of two consecutive coils must be within 3 weldable gauge ranges.

The accuracy of the model for the occurrence of stringers is measured by calculating the occurrence of false positives (model predicts a stringer when no stringer is used), and false negatives (model predicts no stringer when a stringer is used). The table below summarizes the results:

		Actual	
		Stringer	No Stringer
Model	Stringer	96.1%	3.9%
	No Stringer	3.9%	96.1%

Table 10: 91 Line: Validation of Model for the Occurrence of Setups

The symmetry in the table is purely coincidental. The following section describes the model for the duration of the setups.

(b) Model for the Duration of Setups

The shading of the process cycle transitions in the Process Cycle Transitioning Grid (Figure 15) represents the minimum amount of time required to make the change in process parameters. This suggests that there are two types of stringers: 6 and 12 minute stringers. However, an analysis of the duration of the setups does not support this distinction. In fact, the mean duration of the 6 minutes stringers is 18.5 minutes and standard deviation 10.1 minutes. The mean duration of the 12 minute stringers is 17.4 minutes and standard deviation is 7.72 minutes. Furthermore, the 95% confidence interval for the difference of the means of the duration of the setups for 6 minute and 12 minute transitions is

$$-1.84 \leq \mu_6 - \mu_{12} \leq 3.82$$

where μ_6 and μ_{12} are the population means. Since the confidence interval for the difference of the means contains zero, the distinction between 6 and 12 minute stringers is not statistically significant. Consequently, a single model is built to predict the duration of setups for all the possible process cycle transitions. It should be noted that the distinction between 6 minute and 12 minute stringers may become significant in the future. The reason is that since approximately the beginning of November 1997, 91 Line is run under level II control. In level II control, the line speed is automatically adjusted as a function of the stringer length so that the setup time is optimized.

Using the same approach as for 90 Line, assuming that there may be a relationship between setup time and inverse of line speed, the model for setup time is

$$T_i = \alpha_0 + \alpha_1 \cdot \frac{1}{V_i} + \varepsilon_i \qquad i=1,2,\ldots,n$$

where T is the duration of the setup (minutes), V is the final line speed (feet / minute), ε is the error term and i the index ranging over all data points. The coefficients α_0 and α_1 are found by performing a regression of setup time against inverse of final line speed. The data in the regression includes all delay records corresponding to setups (delay codes 11, 106, 109, 373, 380, 512, 513) which did not occur before or after an unexpected delay.

The regression is shown in Figure 16. The sample correlation coefficient is 0.124. Since the F-ratio = 0.57 for the regression is smaller than the critical value F(1%, 1, 624) ~ 6.63, we conclude that $\alpha_1 \sim 0$. The regression is statistically insignificant, thus there is no statistically significant correlation between setup time and inverse of average line speed. In order to confirm this observation, the regression analysis was repeated for the main delay codes separately. The results are summarized in the table below:

Delay Code	F-ratio	Critical 1% F-ratio	Correlation Coefficient	Average Setup Time (minutes)
ALL	0.57	6.6	0.03	18.4
109	6.4	6.9	0.229	18.6
373	0.38	6.6	0.035	18.2
380	0.4	6.9	0.07	16.8

Table 11: 91 Line: Regression Analysis Results for Duration of Setups Model

In all cases, neither the regression, nor the correlation coefficient are significant. Because of lack of correlation between setup time and inverse line speed, and because of the relatively stable average duration of setups, the setup time is modeled has a random variable with constant mean. Its distribution is 0.5 + Gamm(5.14,3.48). The mean is 18.4 minutes and the standard deviation is 7.9 minutes. It is shown in Figure 16.

$$\boxed{\text{Setup Time} \sim 0.5 + \text{GAMM}(5.14, 3.48)}.$$

8.4 Model for Production Time

The model for production time is identical to the one used for the 90 Line simulation model. In summary, the production time is the ratio of the coil length (derived from the coil geometry and weight) and the line speed (derived from the annealing instructions). Given a process cycle and a gauge, the line speed is found by referencing the value for the corresponding 'minutes per inch of thickness'. The reader may refer to Section 7.4 for the description of this model.

To quantify the accuracy of the model, the distribution of the error was found by subtracting predicted production time from the actual production time (i.e. e_i = (actual production time)$_i$ – (predicted production time)$_i$). Only production records that involved process cycles and grades that appear in the simulation model and that did not appear before or after delays were included in the derivation of the error term. The best fit distribution to the histogram of the error term is a normal distribution with mean 1.01 and standard deviation 6.17 minutes.

$$\hat{e} \sim Normal(\mu = 1.01, \sigma = 6.17)$$

The mean of the distribution of the error term is included in the expression for contact time to compensate for the model's tendency to underestimate actual production time:

$$\boxed{\text{Production Time (min)} = \frac{\text{Coil Length (ft)}}{\text{Line Speed (ft/min)}} + 1.01}.$$

Figure 17 compares actual production time with the predicted production time for 400 coils. The graphs show that the predicted production time moves reasonably closely with the actual production time.

8.5 Simulation Logic for No. 91 Anneal and Pickle Line

The simulation model for 91 Line is shown in Figure 18.

(a) Description of Simulation Logic for No. 91 Anneal and Pickle Line

The simulation logic for No. 91 Anneal and Pickle Line is similar to the one used for 90 Line. The actual queue at 91 Line is separated into eleven campaign queues and a twelfth queue. The eleven campaign queues serve the same purpose as the campaign queues in the 90 Line model. However, unlike 90 Line, the campaign groups on 91 Line must be constructed on the basis of both process cycle and pickle group. Henceforth, these eleven queues are referred to as the '91 Line campaign queues'

Once coils from a specific campaign group are selected, the twelfth queue is used to sort them to minimize the occurrence of setups due to changes in gauge or cross section. Unlike 90 Line, the ordering of coils within a 91 Line is done on the basis of cross sectional area because the cross section area rule is more likely to require setups. Henceforth, the twelfth queue is referred to as the '91 Line cross sectional queue'. The logic in VBA1 has been modified to accommodate the new setup rules, and is described in Appendix 2.

The simulation logic for 91 Line is identical to the simulation logic in the 90 Line simulation model (described in section 7.5.a). There is only a slight difference in the campaigning logic, which is described below.

(b) Implementation of the Campaigning Logic

In the simulation logic, entities arrive with an attribute specifying the process cycle the coil is scheduled to undergo and the pickle group. The simulation logic then routes the coil to the appropriate campaign queue according to the campaign groups. The campaign groups are 319-1, 321-1, 367-5, 383-6, 384-2, 444-1, 444-9, 5xx-7, 5xx-9, 516-9, and 538-8. The group 5xx-7 contains the process cycle / pickle group combinations 500-7, 511-7, 532-7, 533-7. The group 5xx-9 contains the process cycle / pickle group combinations 500-9, 511-9, 532-9, 533-9. These two campaign groups are formed by noting from the transitioning grid that no setups for temperature changes are needed for transitions between process cycles 500, 511, 532, 533 and 534. With these groupings, the occurrence of setup rules can be simplified: a setup is necessary for all changes in campaign groups, either because of an acid change or a temperature change. There is one exception to this rule which results from an asymmetry in the transitioning grid: a change from campaign group 321-1 to 319-1 may not require a setup. Within campaign groups, setups can only occur because of cross sectional area rule and/or because of the weldable gauge rule.

8.6 Accuracy & Validation of the Simulation Logic for No. 91 Anneal and Pickle Line Model

(a) Contact Time

The accuracy of the model for calculating production time as a function of coil characteristics and scheduled processing was discussed in Section 8.4. The error term in the model for production time is distributed normally with mean 0 and standard deviation 6.17 minutes. Given that the average processing time on 91 Line is 30 minutes, the standard deviation in the error term corresponds to an error of approximately ± 20%. Furthermore, the visual comparison of actual production time and predicted production time show that the two tend to move together with a reasonable degree of accuracy.

(b) Occurrence and Duration of Setups

The approach used to validate the simulation model is the same as the one used to validate the simulation model for No. 90 Anneal and Pickle Line (see Section 7.6.b). In summary, coils are assigned attributes (width, gauge, weight, and deviation from due date) according to the historical distribution of these quantities. Coils are released into the simulation model such that the frequency of occurrence of the process cycle / pickle group combinations and the average campaign sizes are approximately equal to historical values of these quantities. The historical values of these quantities are shown in the table below. The validation criteria is how closely the simulation predicts the fraction of time spent on setups assuming no unexpected failures and no idle time. The reason for this assumption is simply that the fraction of time spent on failures can easily be adjusted to match the historical numbers by modifying the shape of the failure and repair distributions. The simulation was run for 50 replications of size 100,000 minutes with a warm-up period of 10,000 minutes. One replication takes approximately one minute on a Intel® Pentium 133 MHz computer.

	ACTUAL		SIMULATION			
Campaign Group	Fraction of Coils	Average Campaign Size	Fraction of Coils		Average Campaign Size	
			Lower Limit	Upper Limit	Lower Limit	Upper Limit
319-1	14.5%	9.5	14.7%	15.1%	9.8	9.8
321-1	7.8%	5.6	8.4%	8.7%	6.0	6.0
367-5	9.4%	12.6	8.2%	8.4%	11.0	11.1
383-6	1.1%	3.7	1.5%	1.5%	3.2	3.2
384-2	3.1%	7.7	2.5%	2.5%	6.9	7.3
444-1	2.1%	5.2	1.6%	1.6%	4.1	4.4
444-9	2.1%	3.6	1.6%	1.7%	3.2	3.3
5xx-7	17.0%	12.1	18.2%	18.4%	11.9	12.0
5xx-9	39.2%	16	39.0%	39.5%	16.0	16.0
516-9	1.4%	2.5	1.7%	1.8%	3.0	3.0
538-8	2.4%	8.9	2.7%	2.7%	6.9	7.3

Fraction of Time Spent on*	Actual	Simulation	
		Lower Limit	Upper Limit
Setups	6.5%	5.7%	5.9%
Processing	93.5%	94.3%	94.1%

Table 12: 91 Line: Overall Validation of the Simulation Model

Comparing the '% Occurrence of xxx cycle' and the 'Campaign Size for xxx Cycle' numbers in the above table with the actual numbers shows that simulation was run under conditions similar to the actual conditions. The simulation model predicts a percentage time spent on setups of 5.8%. The actual percentage of time spent on setups is 6.5%. The deviation is less than 1%.

The campaign logic appears to accurately model the occurrence and the duration of setup times. However, we should keep in mind that the model is based on the following exogenous variables: (1) the minimum campaign sizes for each campaign groups, (2) the minimum difference between the earliest due date among all the campaign queues and the earliest due date in the current campaign queue from which campaigns are created.

9. Simulation Model for Z8 Sendzimir Reversing Cold Mill

9.1 General

Since the Sendzimir mill has a discontinuous feed, the production time recorded in the 2000 Character Feedback Records is the sum of contact time and handling time. As described in section 5.3.c, one approach for constructing a model for production time for a discontinuous feed facility is to construct a model for contact time and treat handling time as a random variable whose distribution is the difference of actual production time and contact time. However, in the case of the Sendzimir mill, this approach is jeopardized because production data on contact time is not recorded.

Each time a coil is processed on the mill, the following rolling information about the processing is recorded: on-gauge, off-gauge, time-on, time-off, and number of passes. Contact-on time, contact-off time, and per pass information such as intermediate gauges and rolling speeds are not recorded. Furthermore, the time to process a coil, as expressed by the difference between contact-on and contact-off, contains many other events which occur for every coil and which are not recorded. These events are: slow down at the end of each pass, slow down for the weld, work roll change, inspection of surface quality, load paper. Without per-pass information, it is difficult to quantify the impact of assumptions that need to be made to simplify the task of modeling production time on the mill.

Nevertheless, despite the limitations set by the lack of production data, an attempt was made to build a model for production time on the basis of on-gauge, off-gauge, time-on, time-off, and number of passes.

9.2 Model for Production Time

Production time is the sum of contact time and handling time. Estimating the contact time is a two stage process: First, the number of passes necessary for a given percentage gauge reduction is calculated. Then, the amount of time needed to perform these passes is estimated using an average rolling speed.

(a) Model for the number of passes

The number of passes required to process a coil depends not only on the percentage gauge reduction, width, gauge on, but also on the diameter of the work rolls, the work hardening properties of the steel and the prior processing of the coil (whether or not it was annealed).

The model for the number of passes is based on an analysis of the historical production records. Graphs of the recorded number of passes against recorded percentage gauge reduction are constructed by pooling data for melt codes with the same work hardening properties. For each cluster of data corresponding to a specific number of passes, the median is computed to characterize the central tendency of the data. The median is chosen over the average because of its robustness to outliers. A polynomial is then fitted through the median of the subgroups to characterize the relationship between percentage gauge reduction and number of passes. Given scheduled percentage gauge reduction and meltcode, the simulation can then reference these functions and return the required number of passes.

The graph of number of passes versus actual percentage gauge reduction for all meltcodes within grades 304 and 304L is shown in Figure 19 (the axes on the graph are not shown for confidentiality reasons). These two grades have identical work hardening properties. The distinction between previously annealed and un-annealed coils is not taken into consideration because of the difficulty of tracking the prior processing of coils. Over each cluster of data for a given number of passes, the median (denoted by a circle), the 25% and 75% quartiles (denoted by a the edges of a box) are shown. The boxes contain half of the data points and therefore are a visual measure of the clustering of the data. A third order polynomial is fitted to the medians to obtain a function describing the relationship between Number of Passes and Percentage Gauge Reduction. The model for the number of passes is of the form

$$\text{Number of Passes} = \text{Round}\left(a \cdot r^3 - b \cdot r^2 + c \cdot r - d\right)$$

where r is the percentage gauge reduction and a, b, c, and d are the regression constants.

The predictions of this model are compared to the actual number of passes. The results are summarized below. (Error = predicted number of passes – actual number of passes).

Error	Fraction of Instances
|Error| = 0	76.5 %
|Error| = 1 Pass	22.8 %
|Error| = 2 Passes	0.6 %
|Error| = 3 Passes	0.1 %

Table 13: Z Mill: Accuracy of Model for the Number of Passes

To quantify the accuracy of the model, note that the average duration of a pass is 7 minutes and the average time to process a coil on the mill is 54 minutes, then one pass accounts for approximately 13% of the processing time. For a typical product mix, this model therefore tends to introduce a 13% error for 23% of the instances. The distribution of the percentage gauge reduction for the instances where the error is greater than or equal to one pass (i.e. |Error| ≥ 1 Pass) is shown in Figure 21. The distribution is roughly uniform, with a somewhat greater probability mass for percentage gauge reductions greater than 75%. This is not surprising because the slope of the polynomial increases for higher percentage gauge reductions which increases the probability that the model will incorrectly predict the required number of passes.

Despite the reasonable accuracy of the model for the number of passes, this approach was not pursued for other meltcodes because of the inaccuracy of the model for the rolling speed, which is described below.

(b) Model for the Rolling Speed of the Sendzimir Mill

This section describes a model for contact time using the following variables: gauge-on, gauge-off, time-on, time-off, and number of passes.

Consider the time needed to process a coil scheduled to undergo n passes on the mill. Let g_0 be the on gauge, g_1 be the gauge after the first pass, and g_n the gauge after the n^{th} pass. The time to process one pass is equal to the length of the coil (calculated using the off gauge) divided by the average rolling speed. The total contact time T is the sum of the times needed to perform each pass:

$$T = \frac{d_1}{v_1} + \frac{d_2}{v_2} + \cdots + \frac{d_n}{v_n}$$

where d_i is the length of the coil coming off the mill and v_i is the average rolling speed (as seen by the winding reel) for the i^{th} pass. Since, the v_i's are unknown, it is assumed that there exists an average speed v which satisfies the equation. The total contact time becomes:

$$T = \frac{1}{v} \cdot (d_1 + d_2 + \cdots + d_n) = \frac{1}{v} \cdot A \cdot \left(\frac{1}{g_1} + \frac{1}{g_2} + \cdots + \frac{1}{g_n} \right)$$

where

$$A = \frac{\text{Weight}}{\text{Width} \cdot \text{Density} \cdot 12}.$$

The weight is in pounds, the width and gauge in inches, density in lb/in^3. Since only the on-gauge g_0 and the off-gauge g_n are known, the differences $1/g_i - 1/g_{i+1}$ are assumed to be constant so that the total contact time can be rewritten as

$$T = \frac{1}{v} \cdot A \cdot n \cdot \frac{1}{2} \cdot \left(\frac{1}{g_1} + \frac{1}{g_n} \right)$$

Because of the inverse relationship between g_i and $1/g_i$, the previous assumption implies that the difference $g_i - g_{i+1}$, decreases for each successive pass. This behavior is consistent with the actual process of cold rolling because of the work hardening that is imparted to the metal during each pass.

Taking the inverse of this relationship yields

$$\frac{1}{T} = v \cdot \frac{2}{A \cdot n} \cdot \left(\frac{1}{g_1} + \frac{1}{g_n} \right)^{-1}.$$

Noting that A/g_1 and A/g_n are respectively the length of the coil after the first pass and after the last pass, the average rolling speed v can be found by regressing the inverse of the contact time against the inverse of the average length of the coil. Since g_1 is unknown, it is assumed that $g_1 = (1\text{-}c)\ g_0$, where c is the percentage reduction for the first pass. 'c' is chosen to be 15%. Furthermore, the contact time is unknown so T is approximated using the production time, which includes handling time. In using production time as an estimator of contact time, the speed v now represents an effective average rolling speed such that contact time equals production time.

In order to minimize the introduction of variation external to the model, the data included in the regression is for grades 304 and 304L, which have identical work hardening properties, and only for coils with on-gauge between 0.14 and 0.15 inches. The regression is shown in Figure 20. The 95 % confidence interval for the slope of the regression line, i.e. the effective speed v, is 232 ± 11 feet per minute.

To test the accuracy of the model, the effective rolling speed of 232 ft/min is used to predict the production time from the total rolled length and the actual number of passes. Comparing the predicted production time with the actual production time shows that this model overestimates on average the production of time by 138%. The distribution of the percentage error is shown in Figure 22. The percentage error ranges from -77% to 600%. It is therefore clear that this model for the rolling speed is very inaccurate.

The inaccuracy of this model is attributable to the assumptions that were made as a result of the absence of per pass data. Because of this important limitation, it was assumed that there exists an average rolling speed independent of the number of passes. Furthermore, it was assumed that the differences $1/g_i - 1/g_{i+1}$ are constant. Also, production time had to be used as an estimator of contact time to be able to perform the regression. By showing that the model is inaccurate, we have shown that any one of these assumptions is incorrect. However, because of the lack of per pass data, more specific statements about the impact of these assumptions cannot be made.

Three alternate approaches for modeling production time on the Sendzimir mill are suggested in the following section.

<u>(c) Alternate Approaches to Building a Model for Contact Time</u>

<u>Contact Time Model using Per Pass Data</u>

All the assumptions made in the model described in the previous section were required because of the absence of per pass data. It is therefore reasonable to think that with per pass data, better modeling decisions can be taken and a more accurate model can be constructed. It turns out that there currently exists a system for recording actual per pass rolling data. However, since the system for recording the data is faulty, per pass data is not recorded on an electronic medium.

The advantages to recording per pass data are clear. First, the actual contact time can be calculated and the actual handling time can be inferred. Second, the variation of rolling speed per pass and within passes can be quantified. Third, the percentage gauge reductions as a function of number of passes can by investigated.

Mill Management System (MMS)

Operators of the rolling mill use a program called Mill Management System (MMS) to determine how to process a coil. For a given melt code, work roll diameter, on-gauge and off-gauge, the MMS program returns the gauge reduction and the rolling speed for each pass. MMS has several flaws. It doesn't take into account the following events which occur during the processing of all coils: slow down at the end of each pass, slow down for the weld, work roll change, inspection of surface quality, load paper. Arguably, these flaws are minor since we would expect the slow down in rolling speed to be insignificant compared to the production time of a coil. Furthermore, events such as work roll change could be accounted for separately. Implementation of the MMS model in the simulation is likely to yield an accurate model. However, the level of complexity of the model contained in the MMS software is unknown.

Using MMS to build a simulation model of the mill involves understanding how to translate the MMS code into visual basic code so that it can be integrated into the simulation. Per pass data would also be useful in implementing a model based on MMS instructions because it is currently not possible to quantify how closely MMS instructions are followed by the operators of the mill.

Finite Loading Model

A third approach is to use the model that is used to finite load orders onto the Sendzimir mill. In the finite loading model, IHPT (inch hours per thousands pounds) rates are calculated using the following expression:

$$\text{IHPT Rate} = (\text{Production Hours}) \cdot \frac{\text{Width}}{\text{Weight} / 1000}$$

These rates are calculated for all possible combinations of process code, grades, coil width ranges (7 inch intervals) and gauge off ranges (approximately 0.007 inch intervals). On-gauge is not taken into account. There are over 330 rates just for process code 09 ("Final Cold Roll") which accounts for approximately three fourths of the production time on the Sendzimir mill. Beyond the large number of rates, the model has two weaknesses.

First, it categorizes coils by grade and not by melt code. Within grades, the work hardening properties of the metal may vary significantly. This is especially true for grades 201 and 301, which have significantly different work hardening properties depending on the chemistry of the steel. As an example, consider a typical grade 301 coil with the following characteristics: weight = 50,000 lbs., width = 49", on gauge = 0.140", off gauge = 0.040". Then, for melt codes 1110K, 1110S and 1110B, the number of passes and total contact times predicted by MMS to process this coil are respectively {7 passes, 42.8 min}, {8 passes, 47.9}, {9 passes, 52.5}. This suggests that a 20% error in predicted contact time can result from not distinguishing melt codes. A simulation model based on IHPT rates might therefore not be able to accurately model the impact of product mix on production time.

Secondly, the model does not take into account on-gauge. The justification for this is that the on-gauge varies only slightly on the Sendzimir mill. The histogram of the on-gauge for the Sendzimir is shown in Figure 23. The mean is 0.152" and the standard deviation 0.049". To assess the impact of this assumption on the accuracy of the model, consider a typical grade 304 coil, with the following characteristics: weight = 50,000 lbs., width = 49", off gauge = 0.018". Then, for on gauge 0.160", 0.150", 0.140", 0.130", the number of passes and total contact time predicted by the MMS software to process this coil are respectively {12 passes, 90.6 min}, {11 passes, 84.3 min}, {11 passes, 84.5 min}, {11 passes, 83.9 min}. The percentage variation in the predicted contact time is lower than 10%. Thus, the constant on gauge assumption is reasonable.

The accuracy of the finite loading model for the Sendzimir mill was calculated by the comparing the predicted production time with the actual production time for all process code 9 production records. The distribution is shown in Figure 24. The mean and standard deviation of the distribution of the percentage error ((Predicted – Actual) / Actual) are 25% and 41% respectively. An explanation for the nonzero average percent error is that the rates used in the finite loading model are updated only once a year. Hence, these rates do not take into account the learning curve associated with running the mill. As described in section 2.3, a x-factor is used to partially compensate for the 25% mean percentage error.

Building a simulation model on the basis of IHPT rates is quite cumbersome. Over 330 IHPT rates would have to be incorporated into the model simply to account for process code 9. Even simplifying the model to deal with the most common product types may yield over 100 rates. This, combined with a standard deviation of 41% in the percentage error term, does not favor the use of IHPT rates to construct a model of production time for the mill.

10. Conclusions and Recommendations

10.1 General Conclusion

An analysis of the level and variation of WIP at the facility level and the plant level suggested the need for a more responsive inventory control and scheduling policy (Section 1). A distinction was made between scheduled based and state based inventory control and scheduling policies. The implementation of WIP caps was suggested as a means of introducing elements of a state based inventory control and scheduling policy in the current scheduled based policy (Section 2).

Because of the complexities in the manufacturing processes attributable to the breadth of the product mix, and because of the wide range of routings that coils follow, simulation modeling was presented as a tool that can be used to assess the impact of alternate inventory control and scheduling policies. The basic components of a discrete event simulation model were presented (Section 3 and 4).

A method for building the simulation models was outlined (Section 5). Using this method, simulation models for two anneal and pickle lines were constructed (Section 7 and 8). These models were found to be accurate to within 1% in predicting the fraction of time spent on setups relative to the total production time. This shows that the simulation models can accurately capture the impact of product mix and campaigning on production time, and on the occurrence and duration of setups.

An attempt was made to build a model for a Sendzimir mill. However, difficulties attributable to insufficient production data rendered the model very inaccurate. Alternate approaches for building a model for the Sendzimir mill were suggested (Section 9).

The following sections present more specific conclusions and recommendations by topic.

10.2 Simulation Modeling as a Tool for Operations Research

Simulation modeling was presented as a tool that can capture the idiosyncrasies of production facilities in the context of stainless steel manufacturing. The simulation models for the anneal and pickle lines were shown to accurately capture the impact of product mix variation and campaigning on production time and on the duration and occurrence of setups.

More generally, the endeavor of building a simulation model was found to raise questions and uncover potential problems whose resolution can lead to improvements in the management of the manufacturing facilities. In requiring a thorough quantitative understanding of the physical processes, simulation modeling can uncover ways of improving the processes which might not previously have been investigated.

For example, our analysis of the duration of setups on 90 Line indicated that there may be room for improvements in the selection and the availability of stringers for that facility. Under ideal circumstances, there should always be a stringer available to accommodate the setups occurring at different line speeds such that the setup time is equal to the time needed to make the change in the process parameters. There should therefore be no correlation between setup time and inverse of line speed. Having measured a significant correlation coefficient (= 0.6) between these two variables suggests that some improvements may be possible in terms of the selection and availability of stringers on 90 Line.

In making use of large amounts of production data, simulation modeling can create significant incentive on improving and / or maintaining a consistent level of precision and quality in the production data recording systems. There is evidence that the current users of the production data do not create this incentive. First, we found that there was a lack of consistency in the way production data is recorded for different facilities. More precisely, although stringers are recorded as delay records on 90 Line, on 91 Line, stringers are recorded as production records. From an analyst point of view, this means that the programming tools that are created to extract data from the production records of one anneal and pickle line cannot necessarily be carried over to the production data of other anneal and pickle lines.

Also, and given that the Sendzimir mill is a bottleneck facility, the apparent lack of initiative to repair a defective system intended to record per pass data electronically on the Sendzimir mill raises concerns not only about the depth of the analyses that are currently being performed but also about the questions that are not being raised. In fact, we concluded that recording per pass data would not only provide information needed to build an accurate model of the mill, but would also allow to address questions such as: how closely do operators follow the MMS instructions, and how much of the variation in the production time can be attributed to variation in operator skills.

10.3 Suggested Future Work using Simulation Modeling

(a) Suggested Future Work on the Simulation Models for the Anneal and Pickle Lines

There are a number of improvements that can be made to the models of the anneal and pickle lines. However, the complexity of a model should not exceed the requirements set by the project for which the model is intended. The following points are therefore suggestions, but may not be necessary.

- Campaign size logic: The current algorithm calculates campaign size by selecting groups of coils due on the same date starting with the earliest due date and going forward in time until a minimum (user defined) campaign size is reached. An improvement is therefore to replace this logic by one that does not depend on a priori campaign sizes.
- Crew scheduling logic: The simulation software allows to define the capacity of processing resources. Crew scheduling effects can be incorporated into the model by reducing the capacity of the resource to zero at specific times when the facility is not crewed.

- Rework and added operations logic. The simulation software contains simple constructs which can reroute products on the basis of probability distributions to represent the occurrence of unexpected operations.

(b) Predicting the Impact of Alternate Inventory Control and Scheduling Policies

Predicting the impact of alternate inventory control and scheduling policies requires building interconnected models of the facilities contained in the plant. This requires building a routing logic to model the flow of products through the plant. This is a topic which was not investigated in this thesis because we concentrated on the modeling of individual facilities.

Thus, to assess the impact of alternate inventory control and scheduling policies, such as the implementation of WIP caps, it may be reasonable to begin with models much simpler than the ones that have been described in this thesis. One approach is to build models which calculate production time simply on the basis of the average productivity of the facility (in tons per hour) and coil weight. Under these circumstances, a routing logic can be designed without the clutter that would result if logic to capture the impact of product mix, setups and campaigning were also incorporated.

Incrementally, the level of complexity in these simple models can be increased to capture more intricate characteristics of the manufacturing process such as the impact of product mix, and campaigning. At this stage, the constructs and methods described in this thesis should be useful.

(c) Predicting Shifts in Bottlenecks

Since it was demonstrated that the simulation models can capture the impact of product mix on production time, simulation modeling can be used to predict shifts in bottlenecks as a function of product mix. For example, a plant recently received a set of large orders for a specific product type which differed somewhat from the usual product mix. Within a few days, WIP unexpectedly accumulated in front of a perceived non-bottleneck facility. The following explanation was suggested to account for this behavior. Upon receiving the set of orders, the plant was scheduled on the basis of the facility that has historically been the bottleneck. However, because of the significant temporary change in product mix, it is believed that the actual bottleneck shifted and caused WIP to accumulate unexpectedly. If this is in fact what happened, and given that we have shown that simulation modeling can capture the impact of product mix on production time, it is reasonable to think that simulation experiments could have predicted the shift in bottleneck. Consequently, early warnings could have been sent to the individuals responsible for scheduling the plant, and an increase in WIP might have been avoided.

Definitions

2000 Character Feedback Records: The 2000 Character Feedback Records is a database which contains production, delay, man and inspection records for all the facilities within the company. A production record is created every time a coil is processed on a facility. Delay records are created whenever an unexpected delay or a setup occurs. Typical information included in the production records is: Date, Turn, Facility Number, Time-on, Time-off, Gauge-on, Gauge-off, Weight-on, Weight-off, Grade, etc.

Beta Distribution: The Beta probability density function has two parameters α and β, and is given by

$$f(x) = \begin{cases} \dfrac{x^{\beta-1} \cdot (1-x)^{\alpha-1}}{B(\beta,\alpha)} & \text{for } 0 < x < 1 \\ 0 & \text{otherwise} \end{cases} \quad \text{where } B(\beta,\alpha) = \int_0^1 t^{\beta-1} \cdot (1-t)^{\alpha-1}\, dt$$

The mean and variance of Beta probability density function are $\dfrac{\beta}{\beta+\alpha}$ and $\dfrac{\beta \cdot \alpha}{(\beta+\alpha)^2 + (\beta+\alpha+1)}$ respectively.

Contact Time: Contact time is the amount of time that jobs spend on a facility. It is defined as the difference between 'contact-off' and 'contact-on'. Contact-on is recorded when the coil comes into contact with the winding reel. Contact-off is recorded when the coil is completely wound on the winding reel. Contact-on and contact-off are not recorded in the 2000 Character Feedback Records.

Cycle Time: The average cycle time for a routing is the sum of the average cycle times for the stations on the routing. For each station, the average cycle time is the sum of queue time, process time, wait for batch time, move time.

Gamma Distribution: The Gamma probability density function has two parameters α and β, and is given by

$$f(x) = \begin{cases} \dfrac{\beta^{-\alpha} \cdot x^{\alpha-1} \cdot e^{-x/\beta}}{\Gamma(\alpha)} & \text{for } x > 0 \\ 0 & \text{otherwise} \end{cases} \quad \text{where } \Gamma(\alpha) = \int_0^\infty t^{\alpha-1} \cdot e^{-t}\, dt$$

The mean and variance of Gamma probability density function are $\alpha\beta$ and $\alpha\beta^2$, respectively.

Gauge: Thickness of sheet steel.

Grade: The chemistry of stainless steels can vary in many ways. The variations in the chemistry characterize the different grades of steel. All stainless steel grades contain a sufficient amount of chromium ($\geq$10%) to render the steel corrosion resistant. However, the chromium content may vary substantially, leading to different degrees of resistance to corrosion and oxidation. There are three groups of grades: (1) the Chromium group (400 series), (2) the Chrome-Nickel group (300 series), and (3) the Chromium-Nickel-Manganese group (200 series).

Handling Time: The handling time is the time needed place a coil on the payoff reel, and the time need to remove the coil from the winding reel and to weigh it. Handling time is not recorded in the 2000 Character Feedback Records.

Linear Congruential Generator: A linear congruential generator (LCG) is a method for generating a stream of uniformly distributed random numbers. The stream of numbers Z_1/m, Z_2/m, …,Z_n/m is created using a recursive equation of the form

$$Z_i = (a \cdot Z_{i-1} + c) \bmod m$$

where a, c, m are constants and Z_0 is the seed. Since the Z_i's are the remainder of a division by m, so $Z_i \in [0, m\text{-}1]$. To get a stream of numbers between 0 and 1, the Z_i's are divided by m. The value of the constants a and c are chosen both on theoretical and empirical grounds. Since the recursive equation only depends on the previous remainder, the stream of numbers Z_i will repeat itself as soon as a previously generated Z_i is encountered. Since m is equal to the number of different values that the Z_i can take, m sets the maximum cycle length. Thus, m is typically chosen to be a very large number such as $2^{31} - 1$.

Move time: Move time is the time entities spend being moved between workstations.

Process Cycle: A process cycle refers to specific settings of process parameters on Anneal and Pickle lines. These process parameters may be any or all of the following: furnace temperatures, acid concentrations, line speed.

Production Minutes: Production minutes is a quantity recorded in the 2000 Character Feedback Records. It is defined as the difference between 'time-off' and 'time-on'. 'Time-off' is the time at which the coil as been removed from the winding reel and weighed. 'Time-on' is equal to the 'Time-off' of the previous coil. Production minutes are also referred to as production time.

Production time: See Production Minutes.

Queue Time: Queue time is the time that entities spend waiting for processing.

Scheduled Based Inventory Control and Scheduling Policy: Scheduled based inventory control and scheduling policies release jobs according to a daily production schedule.

State Based Inventory Control and Scheduling Policy: State based inventory control and scheduling policies release jobs on the basis of the state of the manufacturing system.

Stringers: Stringers are scrap coils that are used on anneal and pickle lines to allow time for changes in process parameters so that coils are not over- or under- annealed.

Wait for batch time: Wait for batch time is the time entities spend waiting to form a process batch or a campaign.

Weibull Distribution: The Weibull probability density function has two parameters α and β, and is given by

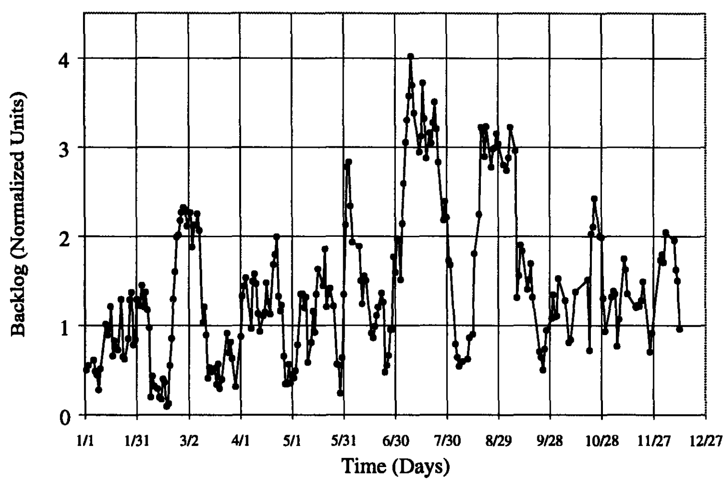
$$f(x) = \begin{cases} \alpha \cdot \beta^{-\alpha} \cdot x^{\alpha-1} \cdot e^{-(x/\beta)^{\alpha}} & \mathit{for}\ x > 0 \\ 0 & \mathit{otherwise} \end{cases}$$

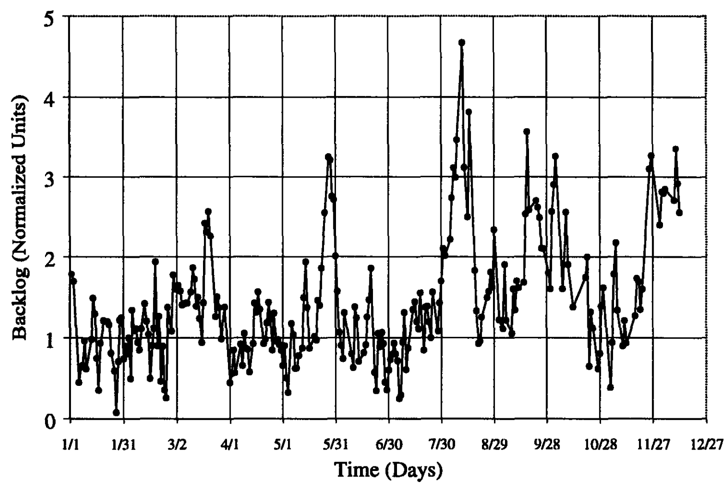
The mean and variance of Weibull probability density function are

$\frac{\beta}{\alpha} \cdot \Gamma\left(\frac{1}{\alpha}\right)$ and $\frac{\beta^2}{\alpha} \cdot \left\{ 2 \cdot \Gamma\left(\frac{2}{\alpha}\right) - \frac{1}{\alpha}\left[\Gamma\left(\frac{1}{\alpha}\right)\right]^2 \right\}$ respectively, where Γ is the complete gamma function (see Gamma distribution).

Width: Lateral dimensions of rolled steel.

Figure 1: Backlog Graphs for Three Facilities (Year 1997)





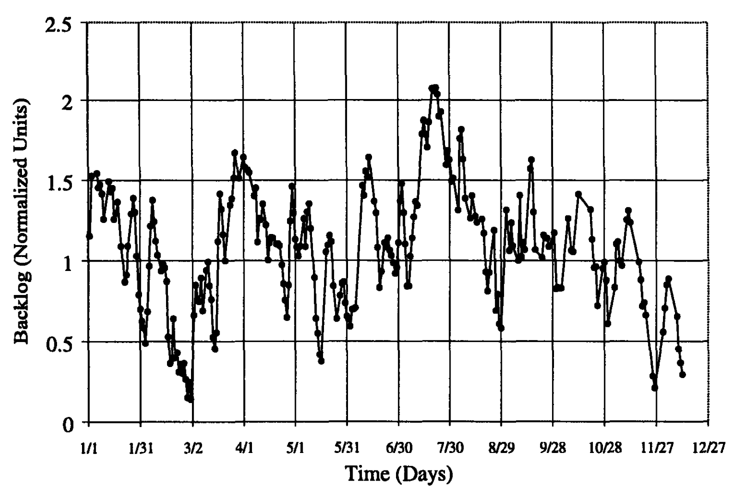


Figure 2: Total Backlog for the Plant (Year 1997)

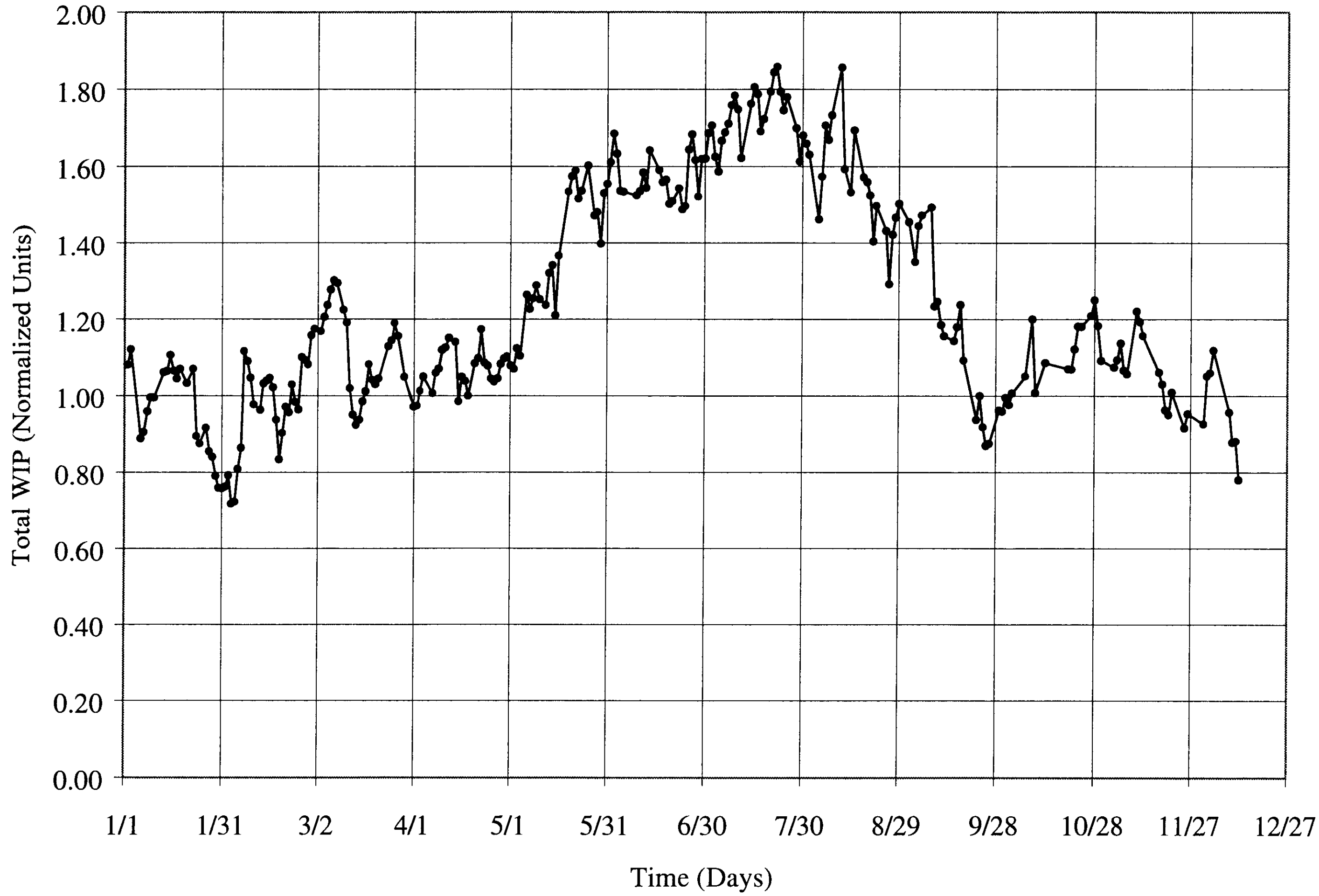
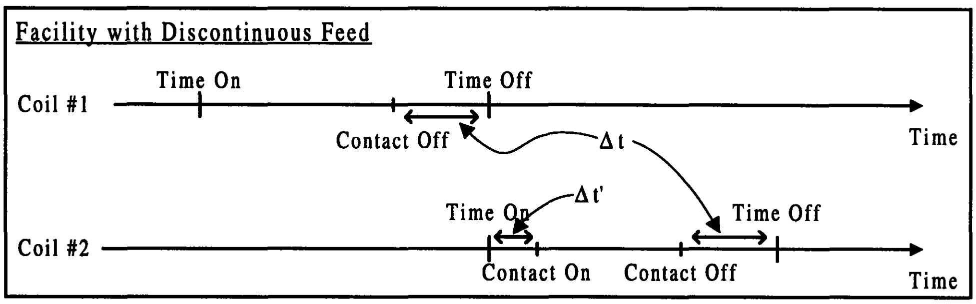


Figure 3: Interpretation of "Production Minutes" Field in 2000 Character Feedback Records

The relationship between contact time, handling time, and 'Production Minutes' depends on whether the facility in question has a continuous feed (e.g. anneal and pickle line) or a discontinuous feed (e.g. Send-zimir mill). In the following figures, time-on and time-off represent the recording of time for the production minutes. Contact-on and contact-off represent the recording of time for the contact time.



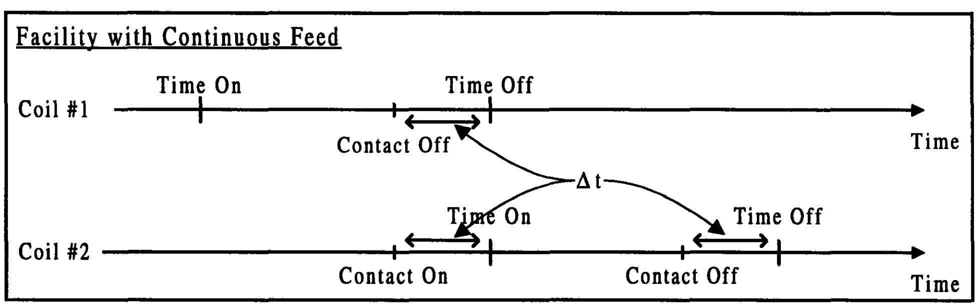
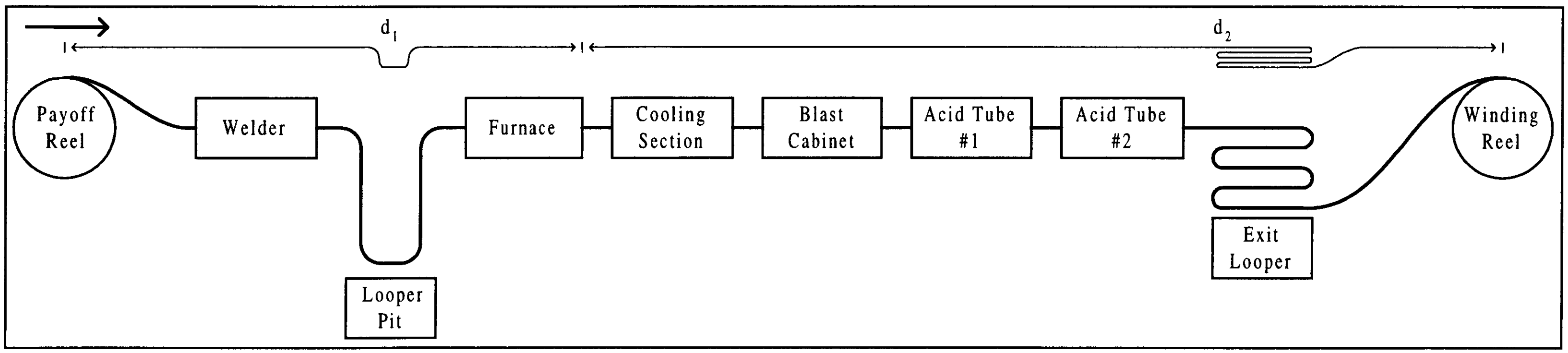


Figure 4: Schematic of 90 Line and 91 Line

No. 90 Anneal and Pickle Line



No. 91 Anneal and Pickle Line

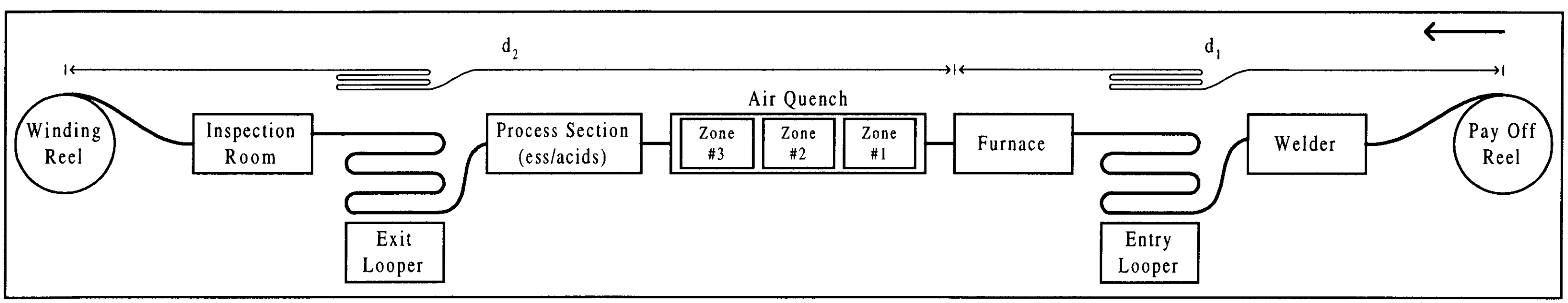


Figure 5: Schematic of Sendzimir Mill

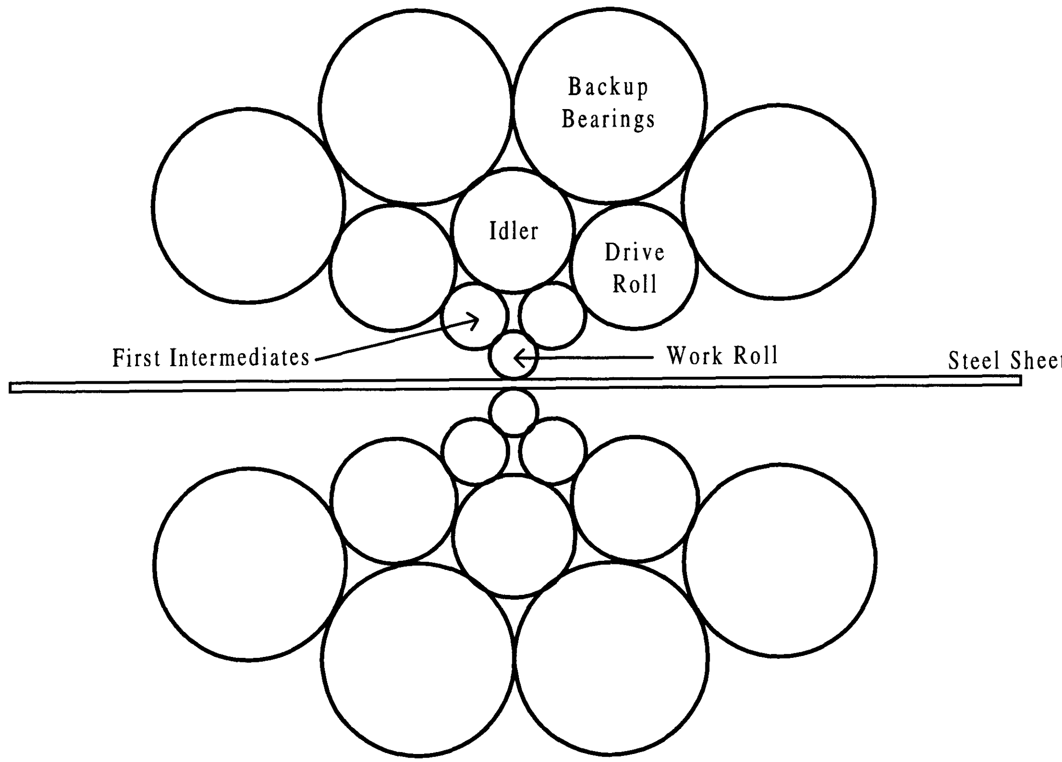
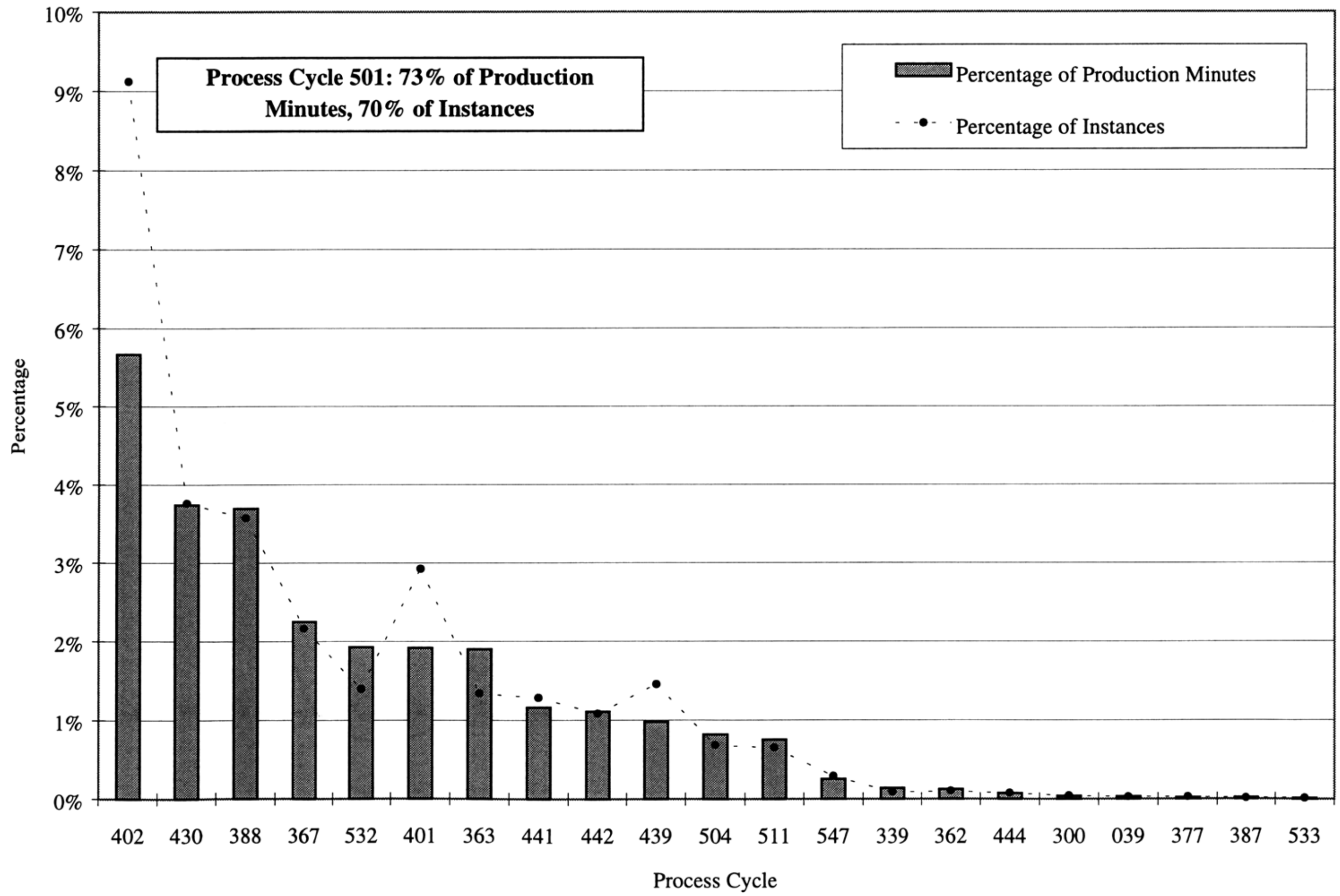


Figure 6: 90 Line: Frequency Distribution of Cycle Codes (Period 01/01/97 - 07/31/97)



<u>Figure 7</u>: 90 Line: Frequency Distribution of Delay Codes by Time and Instance

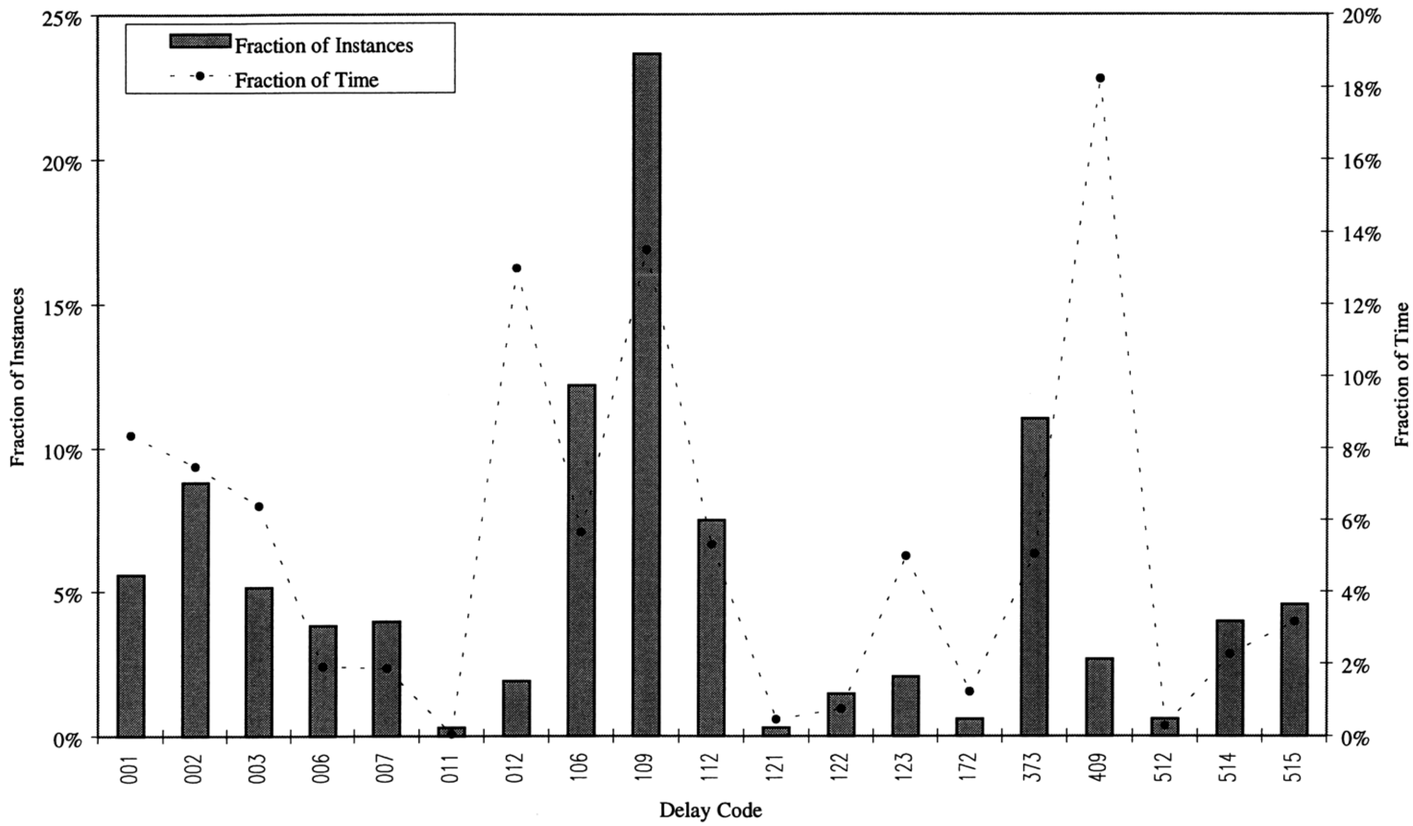
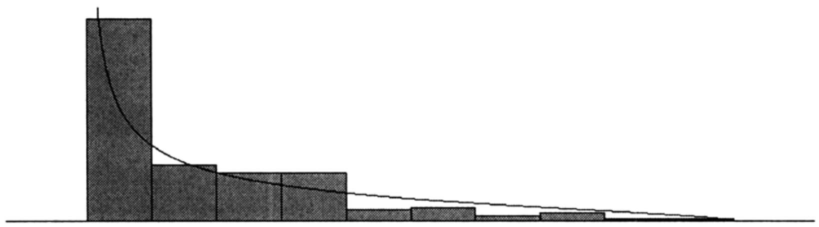


Figure 8: 90 Line: Time to Fail and Time to Repair Distributions

TIME TO FAIL (Minutes)



Distribution Summary

Distribution: Beta
Expression: 9610 * BETA(0.449, 1.55)
Square Error: 0.004419

Chi Square Test
Number of intervals = 6
Degrees of freedom = 3
Test Statistic = 13.1
Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
Test Statistic = 0.136

Corresponding p-value < 0.01

Data Summary

Number of Data Points = 142
Min Data Value = 0
Max Data Value = 9610
Sample Mean = 1740
Sample Std Dev = 1920

Histogram Summary

Histogram Range = -0.001 to 9610
Number of Intervals = 10

TIME TO REPAIR (Minutes)

Distribution Summary

Distribution: Weibull
Expression: WEIB(69.3, 0.641)
Square Error: 0.002362

Chi Square Test
Number of intervals = 4
Degrees of freedom = 1
Test Statistic = 4.91
Corresponding p-value = 0.0274

Kolmogorov-Smirnov Test
Test Statistic = 0.099
Corresponding p-value = 0.118

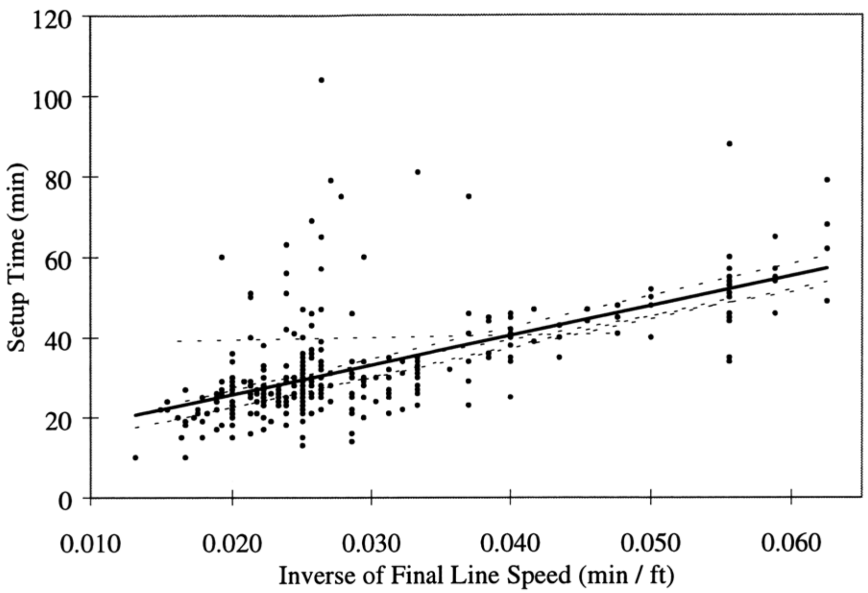
Data Summary

Number of Data Points = 142
Min Data Value = 0
Max Data Value = 1000
Sample Mean = 95.9
Sample Std Dev = 160

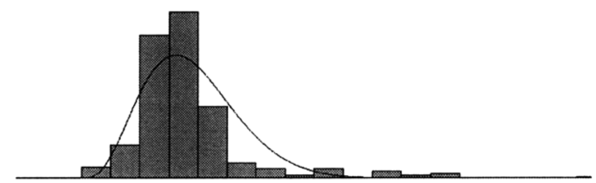
Histogram Summary

Histogram Range = -0.001 to 1000
Number of Intervals = 15

Figure 9: 90 Line: Regression of Setup Time against Inverse of Final Line Speed



	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	10.9	1.7	6.5	3.1E-10	7.6	14.2
X Variable	741.8	54.8	13.5	1.2E-33	634.0	849.6



Histogram of Residuals ε_I

```
                Distribution Summary

Distribution:  Beta
Expression:    -19 + 93 * BETA(4.26, 16)
Square Error:  0.028783
Number of Data Points  = 341
Min Data Value         = -18.1
Max Data Value         = 73.6
Sample Mean            = -6.45e-011
Sample Std Dev         = 10.6
```

Regression Statistics	
Multiple R	0.6
R^2	0.4
Adjusted R^2	0.3
Standard Error	10.6
Observations	341.0

ANOVA	df	SS	MS	F
Regression	1	20676.3	20676.3	183.2
Residual	339	38267.0	112.9	
Total	340	58943.3		

Figure 10: 90 Line: Comparison of Actual Production Time and Calculated Contact Time

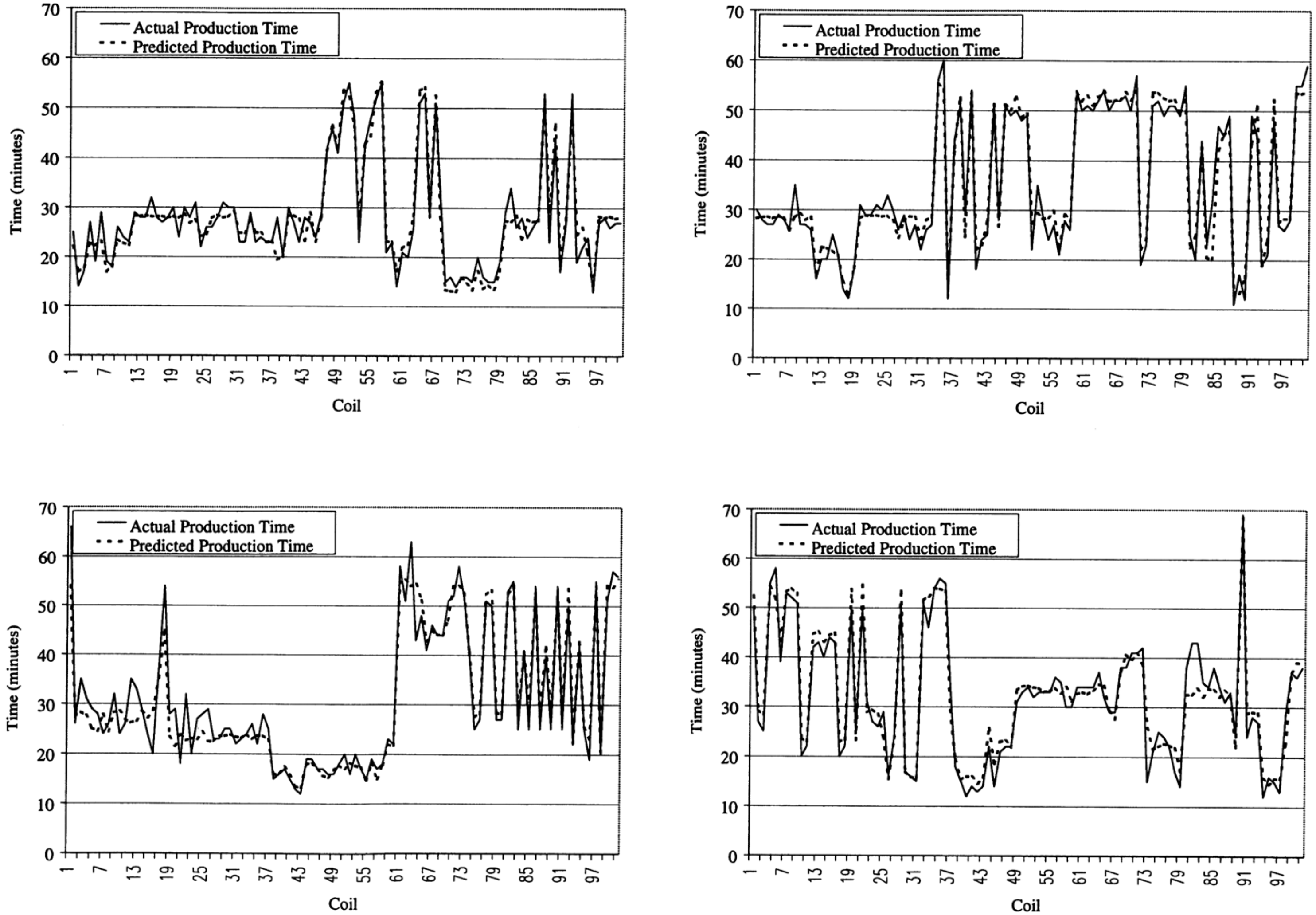


Figure 11: 90 Line: Simulation Model

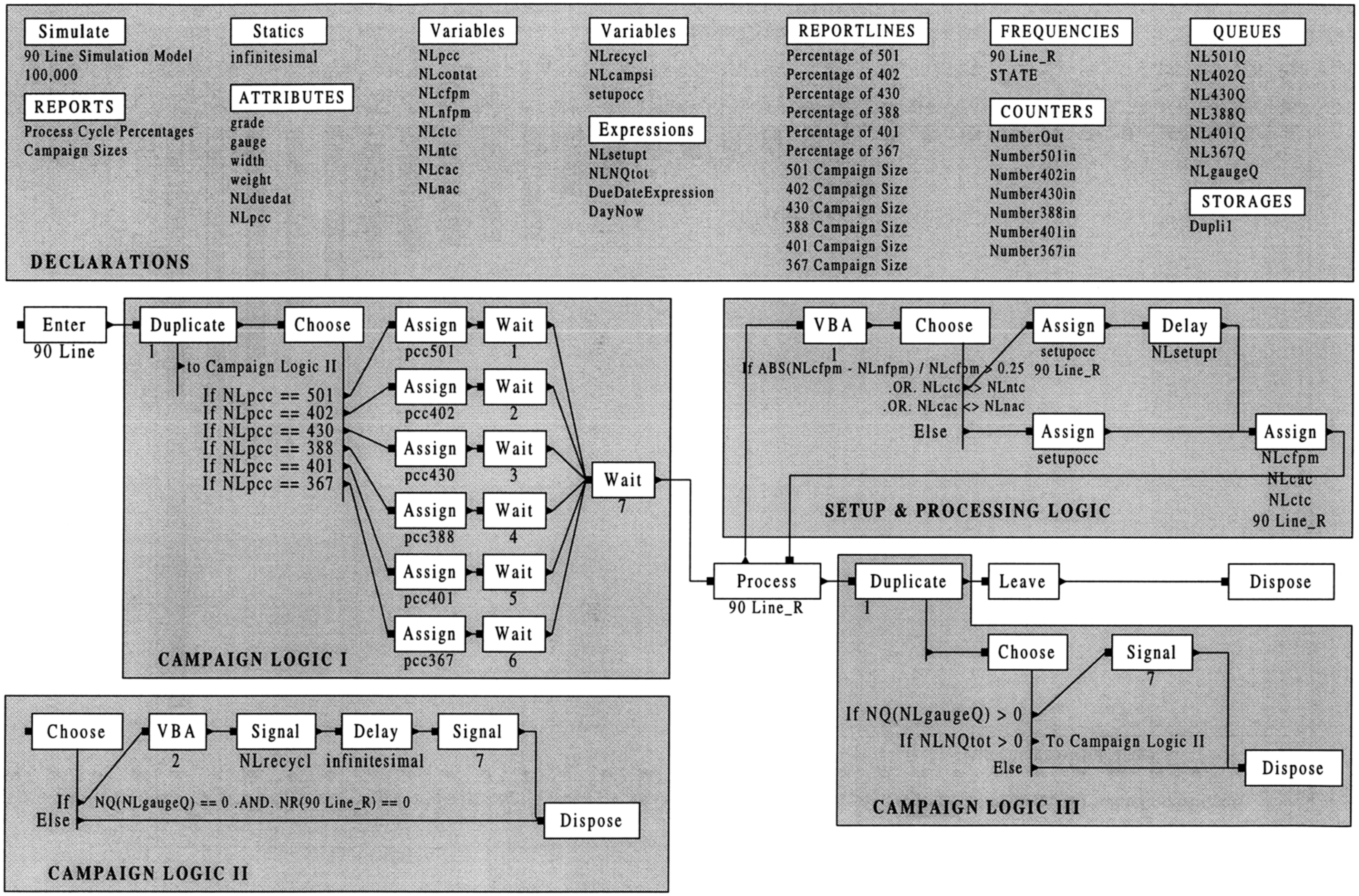


Figure 12: 91 Line: Frequency Distribution of Cycle Codes (Period 01/01/97 - 09/30/97)

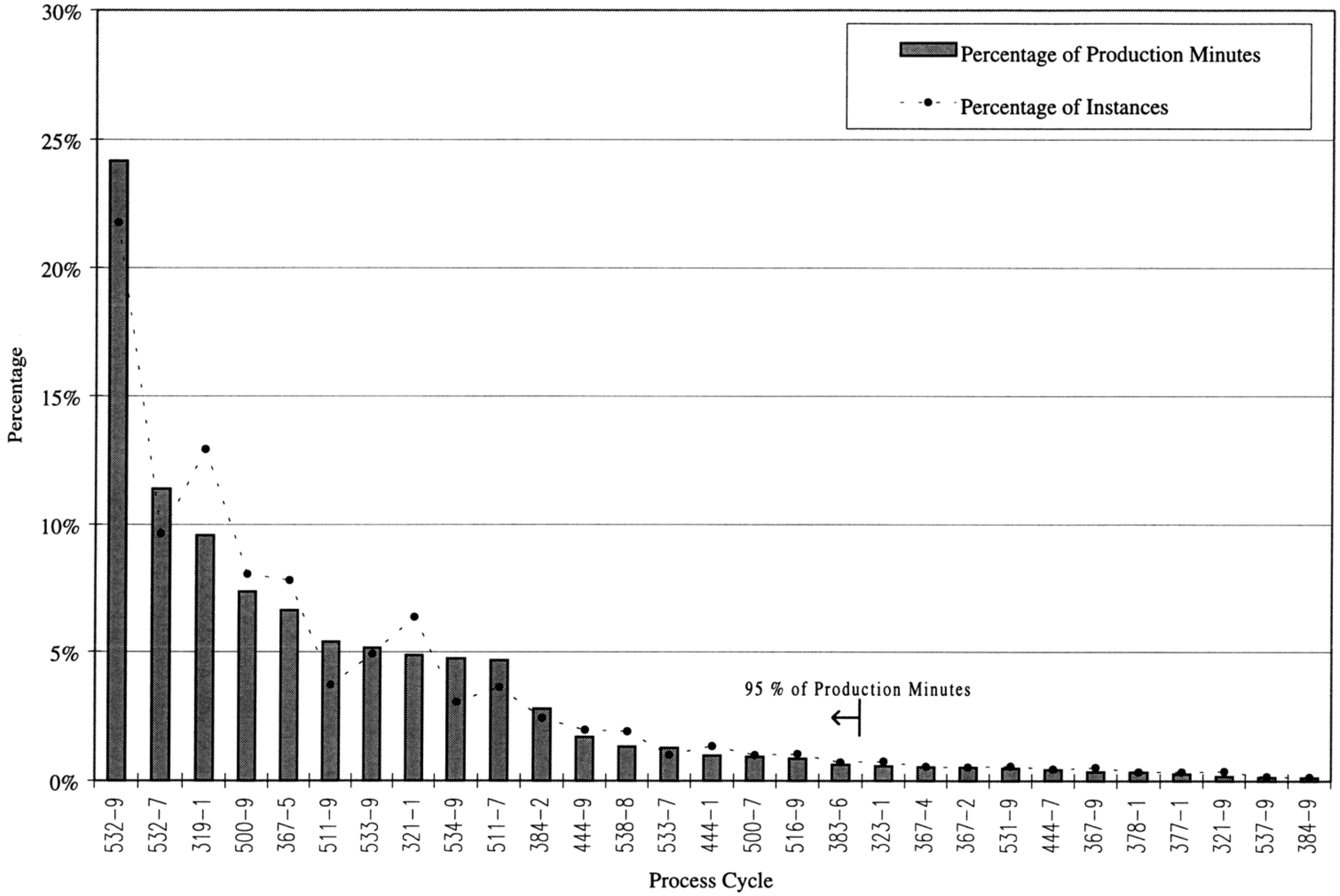


Figure 13: 91 Line: Occurrence of Delay Codes (Period 1/1/97 to 9/30/97)

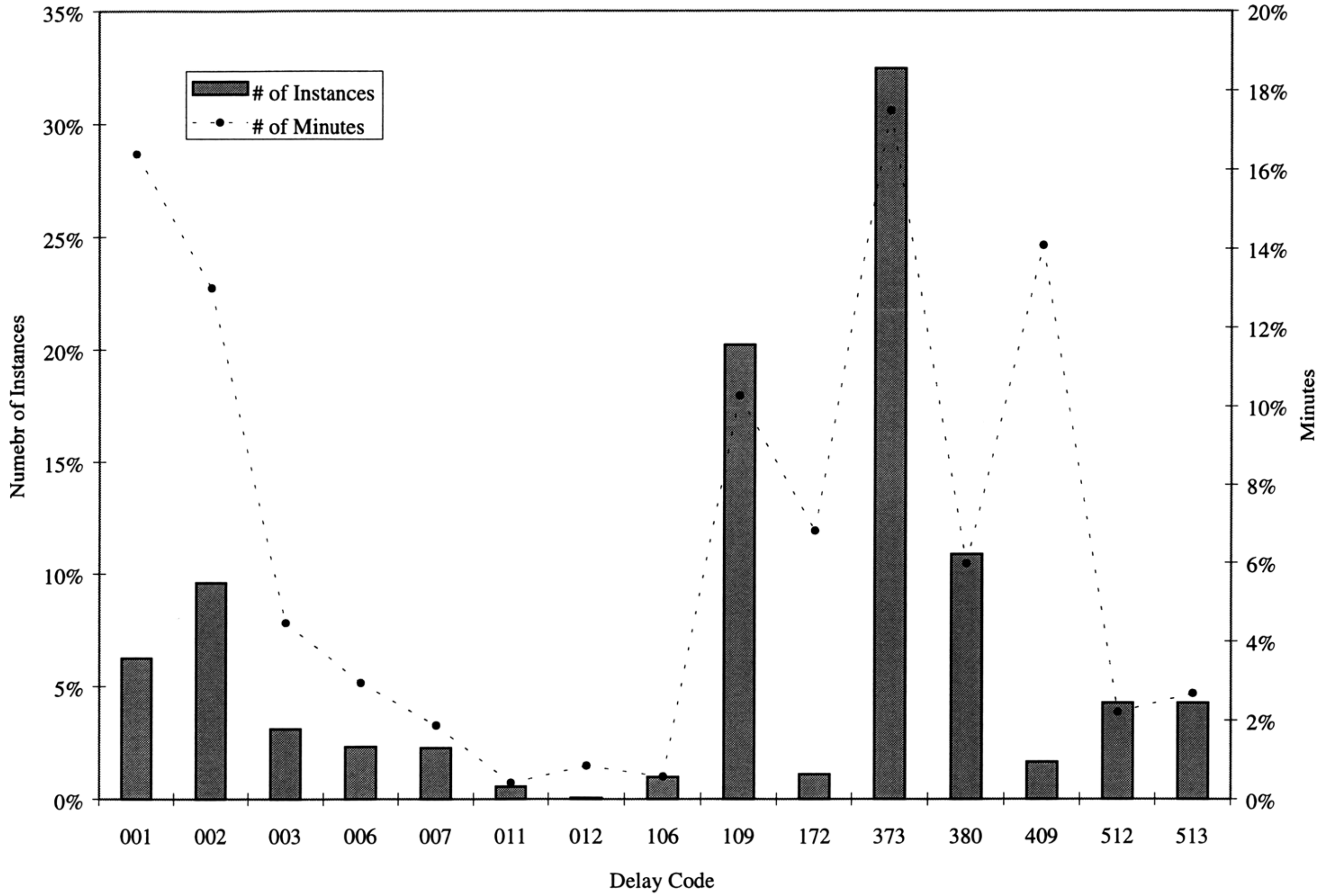
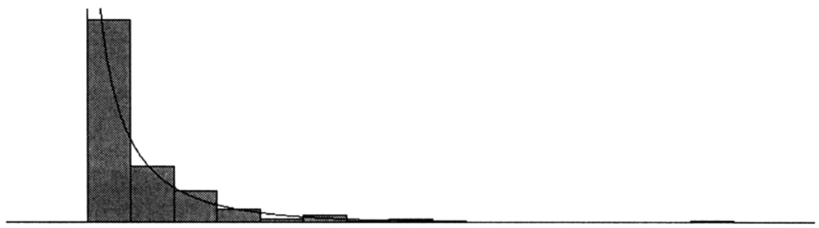


Figure 14: 91 Line: Time to Fail and Time to Repair Distributions

TIME TO FAIL (Minutes)



Distribution Summary

Distribution: Weibull
Expression: 5 + WEIB(1090, 0.701)
Square Error: 0.001222

Chi Square Test
Number of intervals = 5
Degrees of freedom = 2
Test Statistic = 2.04
Corresponding p-value = 0.381

Kolmogorov-Smirnov Test
Test Statistic = 0.0302
Corresponding p-value > 0.15

Data Summary

Number of Data Points = 253
Min Data Value = 5
Max Data Value = 17400
Sample Mean = 1370
Sample Std Dev = 1980

Histogram Summary

Histogram Range = 5 to 17400
Number of Intervals = 15

TIME TO REPAIR (Minutes)

Distribution Summary

Distribution: Weibull
Expression: 4 + WEIB(70.4, 0.721)
Square Error: 0.001489

Chi Square Test
Number of intervals = 3
Degrees of freedom = 0
Test Statistic = 1.98
Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
Test Statistic = 0.0775
Corresponding p-value = 0.093

Data Summary

Number of Data Points = 253
Min Data Value = 4
Max Data Value = 2000
Sample Mean = 93.8
Sample Std Dev = 171

Histogram Summary

Histogram Range = 4 to 2000
Number of Intervals = 15

Figure 15: 91 Line: Process Cycle Transitioning Grid (Excerpt)

TO:

FROM: Cycle	319	321	344/384	367	383	444	511/532	516	533	534	538/529
319		SPEED	ACID	ACID	ACID	ACID?	ACID	ACID	ACID	ACID	ACID
321	SPEED		ACID	ACID	ACID	ACID?	ACID	ACID	ACID	ACID	ACID
344/384	ACID	ACID		ACID	ACID	ACID?	ACID	ACID	ACID	ACID	ACID
367	ACID	ACID	ACID		ACID	ACID?	ACID	ACID	ACID	ACID	ACID
383	ACID	ACID	ACID	ACID		ACID?	ACID	ACID	ACID	ACID	ACID
444	ACID?	ACID?	ACID?	ACID?	ACID		ACID?	ACID?	ACID?	ACID?	ACID?
511/532	ACID	ACID	ACID	ACID	ACID	ACID?		ACID?	ACID?	ACID?	ACID?
516	ACID	ACID	ACID	ACID	ACID	ACID?	ACID?		ACID?	ACID?	ACID?
533	ACID	ACID	ACID	ACID	ACID	ACID?	ACID?	ACID?		ACID?	ACID?
534	ACID	ACID	ACID	ACID	ACID	ACID?	ACID?	ACID?	ACID?		ACID?
538/529	ACID	ACID	ACID	ACID	ACID	ACID?	ACID?	ACID?	ACID?	ACID?	

= 12 MINUTE STRINGER

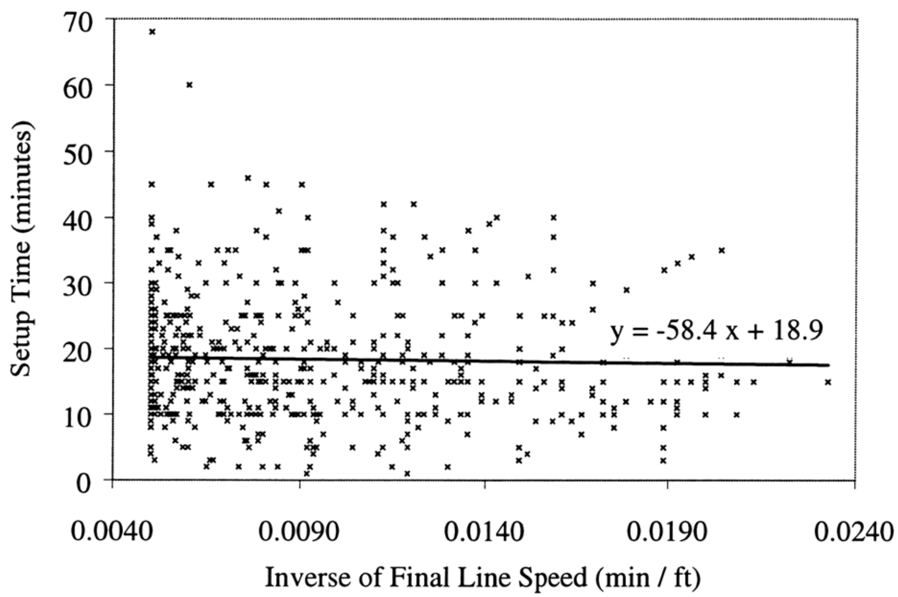
= 6 MINUTE STRINGER

= NO STRINGER

REPICKLE MATERIAL REQUIRES A LONGER STRINGER TIME BECAUSE OF LARGE TEMPERATURE CHANGES

Figure 16: 91 Line: Model for the Duration of Setups

Regression of Setup Time against Inverse of Final Line Speed

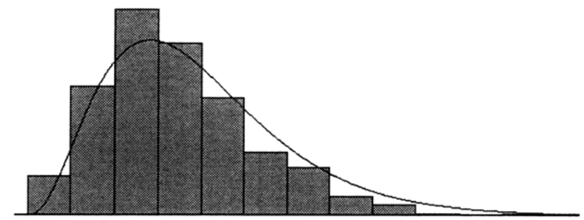


Regression Statistics	
R	0.03
R^2	0.001

ANOVA	DF	SS	MS	F
Regression	1	47.8	47.8	0.57
Residual	624	51668	83	
Total	625	51716		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	19	0.831	23	<.00001	17.3	20.6
X Variable	-58.4	76.8	-0.7	0.4476	-209	92

Distribution of Setup Time (minutes)



Distribution Summary

Distribution: Gamma
Expression: 0.5 + GAMM(5.14, 3.48)
Square Error: 0.001017

Chi Square Test
Number of intervals = 9
Degrees of freedom = 6
Test Statistic = 10.3
Corresponding p-value = 0.118

Data Summary

Number of Data Points = 626
Min Data Value = 1
Max Data Value = 68
Sample Mean = 18.4
Sample Std Dev = 9.1

Histogram Summary

Histogram Range = 0.5 to 68.5
Number of Intervals = 15

<u>Figure 17</u>: 91 Line: Comparison of Actual Production Time and Calculated Contact Time

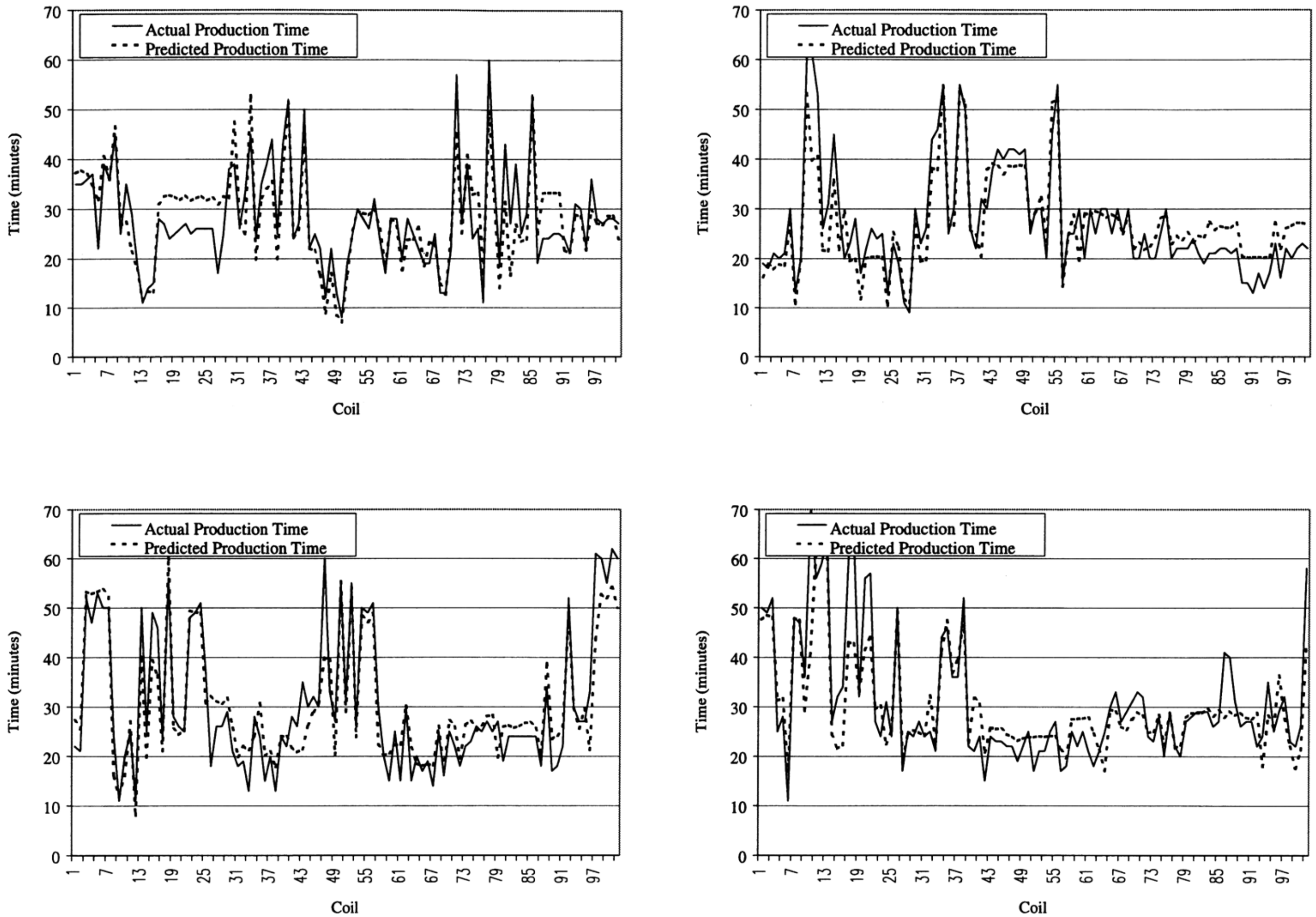
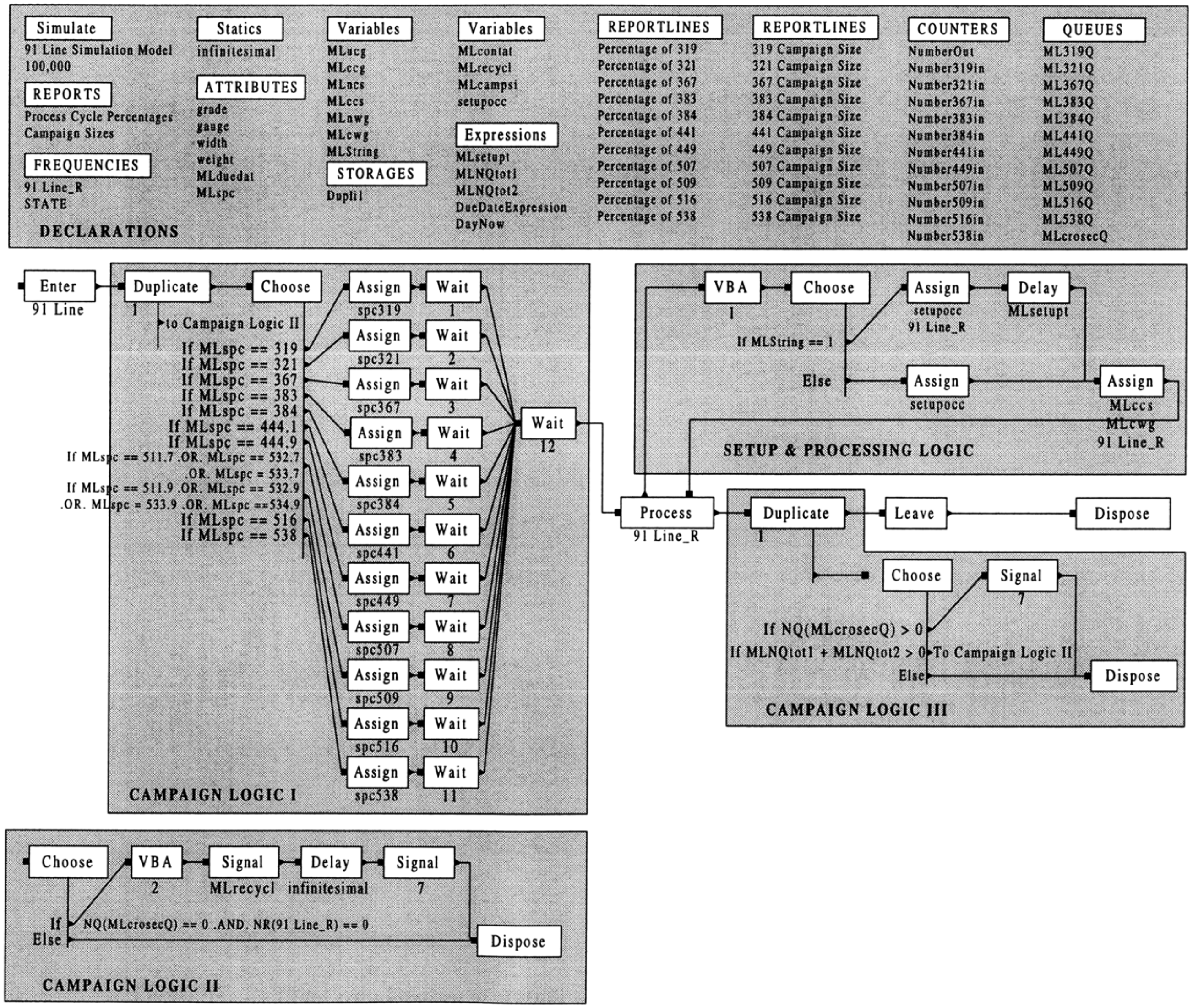


Figure 18: 91 Line: Simulation Model



<u>Figure 19</u>: Z Mill: Number of Passes Versus Percentage Gauge Reduction
Grade 304 and 304L, All Melt Codes

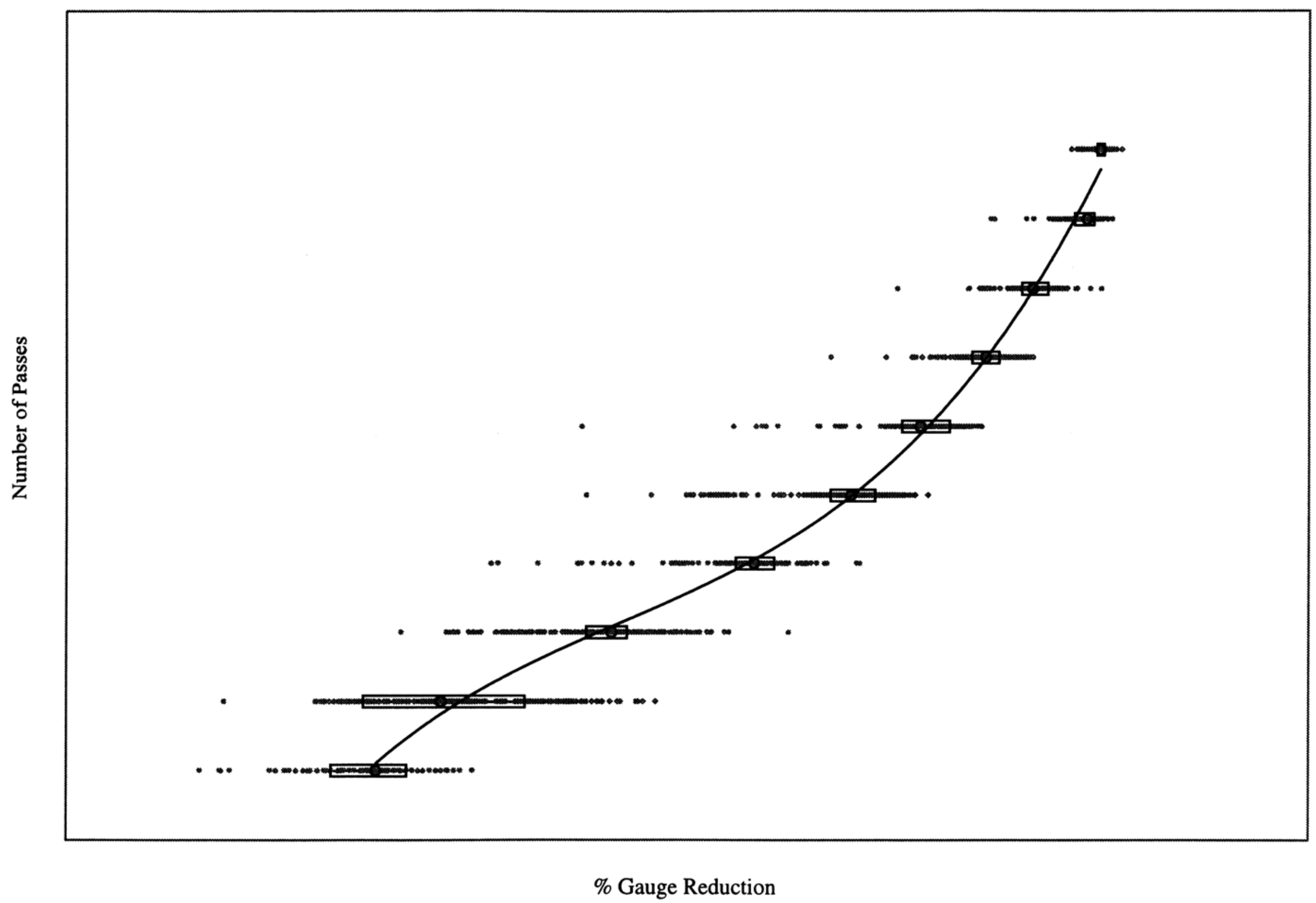
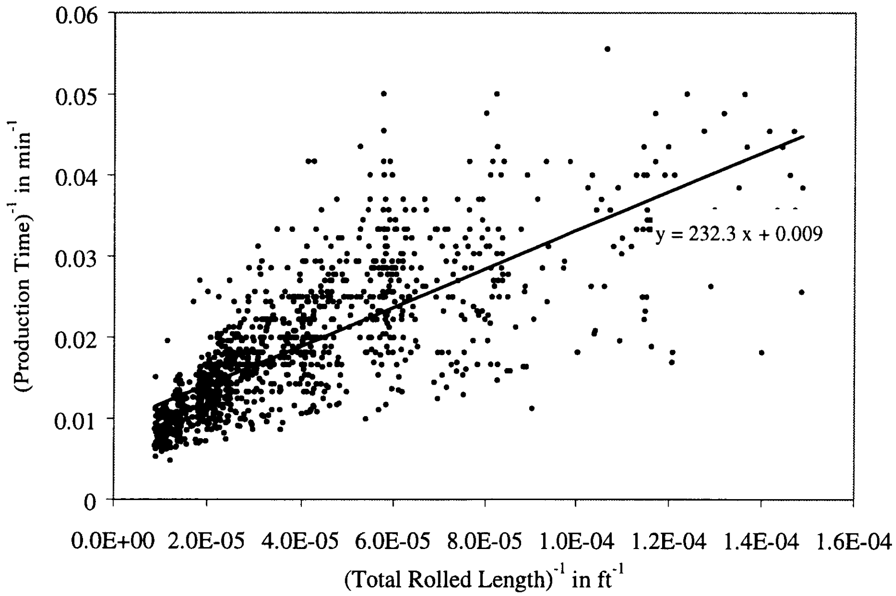


Figure 20: **Z Mill: Regression of Inverse of Production Time against the Inverse of the Total Rolled Length**



Regression Statistics	
R	0.759
R^2	0.577
Adjusted R^2	0.576

ANOVA	df	SS	MS	F
Regression	1	0.053	0.053	1620
Residual	1189	0.039	3.25E-05	
Total	1190	0.091		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.009	2.90E-04	0.009	32.3	0.009	0.01
X Variable	232.3	5.7	0.76	40.3	221	243.6

Figure 21: Z Mill : Error in Model for Number of Passes

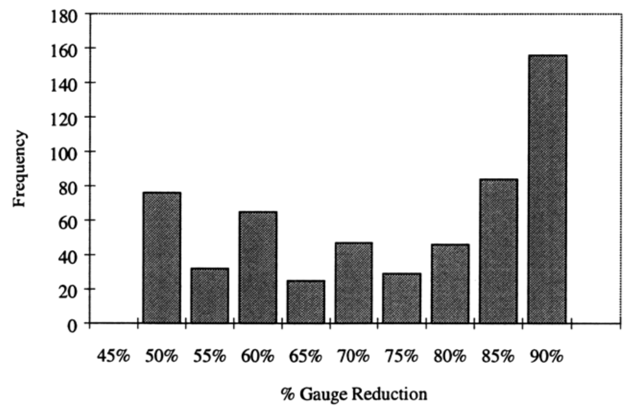


Figure 22: Z Mill : Error in Average Rolling Speed Model

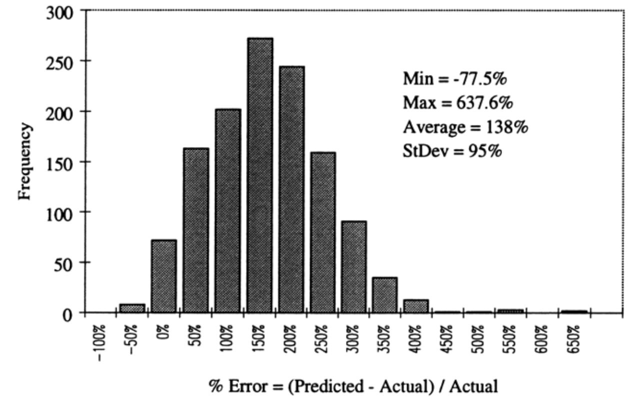


Figure 23: Z Mill: Histogram of On Gauge

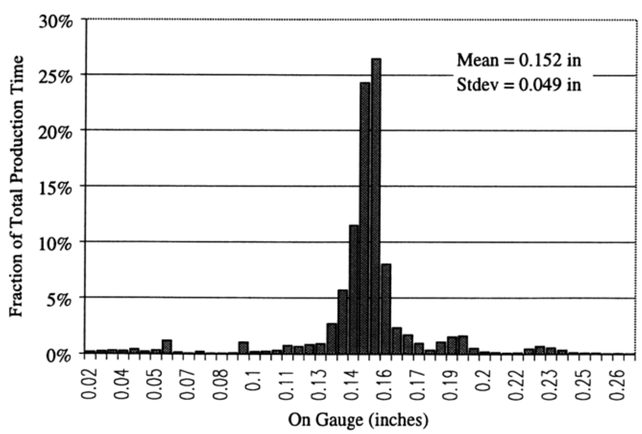
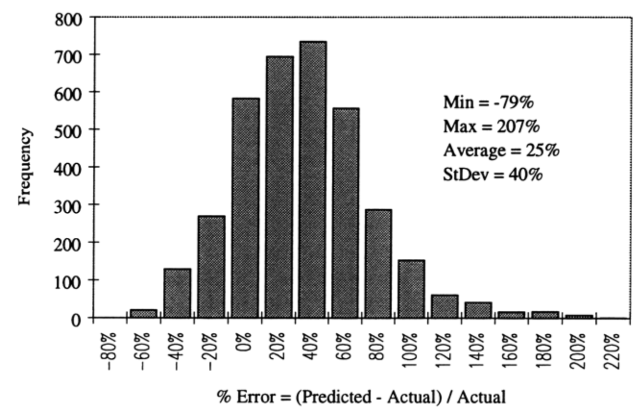


Figure 24: Z Mill: Accuracy of Finite Loading Model



A1. Appendix 1: Routing Analysis

In order to find the routings of coils within the plant, a file is constructed containing all the processing that coils underwent during two separate months. Sorting this file by coil number, processing date, and on-time rearranges the processing of each coil chronologically in time. To find the frequency of occurrence of different routings, a filter is applied to extract the routings of each coil. To simplify the output of the extraction process and to deal with the formation of mults at slitting facilities and to remove routings affected by rework operations, the following rules are incorporated in the filter:

1. If a routings contains two successive identical facilities, skip the second redundant facility.
2. If the coil entering the plant is a mult, discard the routing.
3. If a coil is slit into mults, extract the routing up to and including the A mults of the coil.
4. Once a routing is extracted according to the previous rules, if the routing contains any rework operations, discard the routing.

To illustrate the application of these rules, the routings of two coils that received processing in the plant are shown below:

Coil #	Facility #
01017C154	650108
01017C154	684290
01017C154	689000
01017C154	650108
01017C154	684191
01017C154	684500
01017C154	686202
01017C154	688000

Coil #	Facility #
01017N427	650108
01017N427	683900
01017N427	684290
01017N427	684300
01017N427A	686500
01017N427AA	686500
01017N427AA	689000
01017N427AA	650108
01017N427AA	687006
01017N427AB	686500
01017N427AB	689000
01017N427AB	650108

Facility numbers 650108 and 689000 correspond to the plant receiving center and shipping center respectively. For coil 01017C154, the filter extracts two routings: 650108-684290-689000 and 650108-684191-684500-686202-688000. For coil 01017N427, the filter extracts the following routing: 650108-683900-684290-684300-686500-689000. The filter extracts the facility 686500 only once because of rule 1. The filter does not extract the routing of the mult 01017N427AA when it reenters the plant because of rule 2. Also, the filter does not extract any of the facilities associated with 01017N427AB because of rule 3.

The results of the routing analysis are shown below.

January	April							
10.7%	2.1%	650108	684290	689000				
9.8%	13.4%	650108	683900	684290	689000			
7.8%	5.7%	650108	686202	688000				
6.0%	4.0%	650108	684191	684500	686202	688000		
4.5%	6.1%	650108	683900	689000				
3.1%	1.6%	650108	684290	686500	689000			
2.9%	2.3%	650108	686101	688000				
2.4%	3.6%	650108	683900	684300	686500	689000		
2.2%	3.7%	650108	684500	686202	688000			
2.1%	<1.0%	650108	683900	684290	684300	684191	688000	
2.0%	4.3%	650108	684191	689000				
1.9%	<1.0%	650108	683900	684290	684300	684191	689000	
1.8%	0.6%	650108	683900	684300	684191	686500	689000	
1.6%	2.8%	650108	684191	686202	688000			
1.6%	2.4%	650108	684290	684191	686500	689000		
1.4%	4.3%	650108	684191	688000				
1.4%	<1.0%	650108	684191					
1.4%	<1.0%	650108	684191	684500	688000			
1.2%	1.7%	650108	683900	684290	684300	684191	686500	689000
1.2%	<1.0%	650108	683900	684290	684300	686500	689000	
*	*	650108	688000	686202				
1.0%	<1.0%	650108	684191	686101	688000			

The table shows the routings sorted in decreasing frequency of occurrence for the month of January. The frequency of occurrence in April is also shown. It is apparent that coils do not follow a general path within the plant. No routing occurs more than 14% of the time within the two months considered. Also, the frequency of occurrence of the routings varies by approximately 60% between January and April. We conclude that no main routing exists.

A2. Appendix 2: Additional Explanations on the Simulation Models of the Anneal and Pickle Lines

A2.1 Nomenclature for Variables and Attributes

Because of the large number of variables that appear in the simulation models, it is useful to define a nomenclature.

(a) Nomenclature

The following nomenclature is used to assign names to the variables within the simulation model. Any variable name regardless of the variable type should be no longer than 6 characters. A facility prefix may be added to a variable name if the variable or attribute is specific to that facility. A suffix Q may be added to a variable name if the variables is related to a queue. Prefixes and suffixes appear in upper case characters. The facility prefixes are "NL" for 90 Line and "ML" for 91 Line.

For the 91 Line simulation model, the following nomenclature is used to convert grades that use both numeric and alphanumeric characters to fully numeric representations that can be used within the simulation models:

xxxDA → xxx.1
xxxL → xxx.2
xxxS → xxx.3
xxxTI → xxx.4

(b) Attributes

Every physical entity in the simulation models carries a set of attributes describing the geometrical characteristics of that entity and the processing it is requesting. These attributes are "grade", "gauge", "width", "weight", "NLpcc" (process cycle requested on 90 Line), "MLpcc" (process cycle requested on 91 Line), "NLduedat" (Difference between the date at which the coil was to be processed and the date it arrived in the queue of 90 Line), and "MLduedat" (Difference between the date at which the coil was to be processed and the date it arrived in the queue of 91 Line).

A2.2 Variables Local to the No. 90 Anneal and Pickle Line Simulation Model

Name	**Type**	**Description**
NLpcc	Attribute	Process Cycle Code which entity is scheduled to undergo
NLduedat	Attribute	Date at which the coil is scheduled to be processed
NLccc	Variable	Current process cycle running on the anneal & pickle line
NLcfpm	Variable	Current feet per minute
NLnfpm	Variable	Next feet per minute
NLctc	Variable	Current temperature category
NLntc	Variable	Next temperature category

NLcac	Variable	Current acid category
NLnac	Variable	Next acid category
NLcontat	Variable	Contact time for the incoming coil
NLrecycl	Variable	Is assigned the queue number from which coils are to be removed
NLcampsi	Variable	Number of coils to be released from the cycle queue
NLNQtot	Expression	Total number of entities in the cycle queue

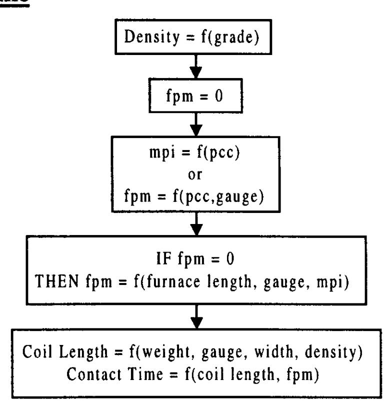
A2.3 Variables Local to the No. 91 Anneal and Pickle Line Simulation Model

Name	**Type**	**Description**
MLspc	Attribute	Process Cycle Code which entity is scheduled to undergo
MLduedat	Attribute	Date at which the coil is scheduled to be processed
MLucg	Variable	Upcoming campaign group
MLccg	Variable	Current campaign group
MLncs	Variable	Next cross section
MLccs	Variable	Current cross section
MLnwg	Variable	Next weldable gauge category
MLcwg	Variable	Current weldable gauge category
MLString	Variable	Boolean variable: = 1 if stringer is necessary, = 0 otherwise
MLcontat	Variable	Contact time for the incoming coil
MLrecycl	Variable	Is assigned the queue number from which coils are to be removed
MLcampsi	Variable	Number of coils to be released from the cycle queue

A2.4 Explanation of VBA1

Upon activation by an entity, a VBA module executes a program written in the Visual Basic® for Applications programming language. This program has three objectives: Calculate the amount of time that the incoming coil will take to process, calculate and compare the process parameter settings requested by the current coil and by the next incoming coil.

(a) Calculation of the Contact Time



VBA1 Programming Logic

The program first calculates the density of the coil. The following rule is used. If the grade is in the 200 series or 400 series the density is 0.28 lb. / in^3. If the grade is in the 300 series then the density is 0.29 lb/in^3.

For the VBA1 module in the 90 Line simulation model, the variable fpm (feet per minute) is initialized to zero. Then, depending on the process cycle which the coil is scheduled to undergo, the minutes per inch of thickness (mpi) or the fpm is computed. The reason for this approach is that depending on the process cycle, the annealing instructions are more easily calculated using minutes per inch of thickness rather than feet per minute.

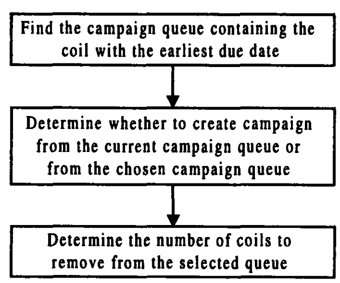
Ultimately the quantity that is calculated is the line speed (fpm). Thus, if after the assignment of one of the two variables, fpm is still zero, this means that mpi was assigned a value. In this case, line speed is calculated as a function of minutes per inch of thickness. Finally, the length of the coil is calculated using the gauge, width, weight and density. The contact time is found from the coil length and line speed.

For the VBA1 module in the 91 Line simulation model, the line speed instructions are all expressed in terms of 'minutes per inch of thickness'.

<u>**(b) Process Parameter Settings**</u>

The VBA1 module also keeps track of the process parameters (temperature settings, acid concentrations, and line speed) requested by consecutive coils. The values of these variables are then compared in the VBA module (for 91 Line) or in the simulation logic (for 90 Line) to determine whether a setup is necessary.

A2.5 Explanation of VBA2



<u>**VBA2 Programming Logic**</u>

When the VBA2 module is activated by an entity, it has already been decided that it is necessary to build a campaign. Thus, the purpose of the VBA2 code is to determine from which campaign group to create a campaign and the size of that campaign.

The campaign queue from which to create a campaign is selected by finding the queue containing the coil with the earliest due date. Since it is possible to have more than one campaign queue with the same earliest due date, ties are broken by considering the number of entities in the queues. If there is still a tie after comparing the earliest due date and the number of entities in each of the campaign queues, then the tie is broken by ranking the campaign groups on the basis of their historical significance in terms of production time.

The campaign size is calculated by selecting groups of coils due on the same date starting with the earliest due date and going forward in time until a minimum (user defined) campaign size is reached.

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